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DOPPLR-A POINT POSITIONING PROGRAM USING INTEGRATED DOPPLER SATELLITE OBSERVATIONS

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APRIL 1976

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This report describes the FORTRAN ~~V~~ 5 program, DOPPLR, developed for use on the UNIVAC 1108 electronic computer. It is designed to derive the position of a receiver observing integrated Doppler shifts in transmissions from an artificial Earth satellite.

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PREFACE

The development of the DOPPLR program was initiated in 1969 to support the U.S. Army Engineer Topographic Laboratories in its analysis of the Doppler Backpack Positioning Equipment with the knowledge that the Geoceiver was being designed as the prime Department of Defense geodetic satellite tracking system. The program has evolved into the main Defense Mapping Agency Topographic Center (DMATC) point positioning routine, and has been used extensively not only for production work, but also in conducting numerous equipment tests and in the analysis of the Navy Navigation Satellite System.

The willing and capable assistance of DMATC employees in the Department of Geodesy, too numerous to mention, is hereby acknowledged.

DOPPLR – A POINT POSITIONING PROGRAM USING INTEGRATED DOPPLER SATELLITE OBSERVATIONS

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SECTION I. INTRODUCTION

1. *DATA REDUCTION*. *a. This report is concerned with the point positioning mode* of reduction of Doppler satellite tracking data. It describes the mathematical development of the pertinent equations and describes the operation of a computer program, DOPPLR, for accomplishing the data reduction.

b. Point positioning uses the Doppler shift of stable signals broadcast from satellites to determine the precise geodetic coordinates of the receiving antenna. Thus, these coordinates are the principal unknowns of the problem, and all known error sources are accounted for in the mathematical model in order to obtain the greatest possible accuracy and precision. Two features distinguish point positioning from other data reduction methods. First, the satellite ephemeris is obtained from some outside source and is held fixed in all computations; second, the solution is made in a multipass mode, involving the simultaneous adjustment of data from many passes of one or more satellites over a single receiving station.

2. DOPPLR PROGRAM. *a.* As a diagnostic aid, the DOPPLR program will perform navigation mode solutions, solving for the receiving station coordinates separately for each satellite pass. The program may also be used in an error analysis mode. In this mode, simulated data are generated and perturbed by specified random and bias errors. The perturbed data are then adjusted to show the effects of the specified error sources.

b. The program operates on integrated range rate data produced by Geoceiver, ITT 5500, and Backpack observing equipment.* Each data point consists of an observed Doppler count, the epoch of the beginning of the count, and the time interval over which the count was accumulated. The program applies necessary corrections for refraction and other effects. A separate preprocessor may be used to put data recorded by various receivers into the proper format for operation of the program.

SECTION II. MATHEMATICAL DEVELOPMENT

3. BASIC CONCEPTS. *a.* Most Doppler receivers work in the same basic way: the received frequency, f_r, is mixed with a locally generated reference frequency, f_0, to produce a beat frequency, f_b. The cycles of this beat frequency are counted from

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* Any mention herein of a commercial product does not constitute endorsement by the U.S. Government.

time T_1 to time T_2. The Doppler count (often called *integrated Doppler count*) is thus:

$$N = \int_{T_1}^{T_2} f_b dt \ .$$

The interval, $\Delta T_g = T_2 - T_1$, over which the Doppler count is accumulated, depends on the type of receiver being used and the mechanization used to produce the time marks T_1 and T_2. The intervals used by existing receivers range from less than 1 second to approximately 2 minutes. The average beat frequency over the interval is $N/\Delta T$. When the interval is sufficiently short, this quantity may be regarded as an approximation of the instantaneous beat frequency and may be ultimately related to range rate.

b. In the DOPPLR program, the observation equation is always written in terms of the Doppler counts, which can be ultimately related to range difference. The exact form of the observation equation depends on the receiver and the source of the time signals. Two sources of time marks are recognized by the program.

(1) The satellite clock is the source of the time signals when Navy Navigation Satellites (NNS [or Navsats]) are tracked. These satellites transmit stable carriers at approximately 400 and 150 megahertz (MHz). Digital data are phase modulated on the carrier at the rate of 6,103 bits per 2 minutes of satellite clock time. The satellite clock is generally kept within 50 microseconds (μs) of Universal Time Coordinated (UTC) by daily monitoring. The format of the digital data repeats every 2 minutes, and the beginning of the format (satellite time mark) may be recognized by a unique bit pattern. Thus, 2-minute intervals may be realized simply by recognizing successive satellite time marks. Shorter intervals may be realized by counting the bits within the 2-minute format. When the appropriate number of bits have been counted by the receiver, a time mark is sent to the Doppler counting circuits. In the receivers considered here, the accumulation of the current Doppler count ends and a new one begins at the first positive-going zero crossing of the beat signal following the reception of the time mark. Thus, no partial cycles of the beat signal are lost between successive counts, and the counts are called *continuously counted integrated Doppler.*

(2) The Doppler beacons in the GEOS (Geodetic Earth-Orbiting Satellite) series of satellites transmit pure tones at approximately 324 and 162 MHz. In this case, the time marks are generated by the local clock. As before, the Doppler counts begin and end at the first positive-going zero crossing of the beat signal following the reception of the locally generated time mark.

c. For both the NNS and the GEOS satellites, the measurement of the Doppler count is made on the higher frequency, while the lower frequency is used only for the computation of ionospheric refraction. Both frequencies of a pair are derived from the same basic oscillator and are coherent at transmission. The actual transmitted frequencies are offset from the nominal values for both satellite types. The offset for the NNS is −80 parts per million (ppm), or −32 kilohertz (kHz) at 400 MHz; for the GEOS satellites, it is −50 ppm, or −16.2 kHz at 324 MHz.

d. For the receivers considered here, the locally generated reference frequencies are the nominal frequencies of 400 MHz for the navigation satellites and 324 MHz for the GEOS satellites. The Doppler shift for an observer fixed on the Earth never exceeds ±20 ppm of the transmitted frequency. Thus, the received frequency (transmitted frequency plus Doppler shift) is always lower than the reference frequency, and the beat frequency is always in the sense $f_b = f_0 - f_r$.

4. BASIC FORMULAS

a. Navigation Satellite Reception

(1) Counting Intervals. For the receivers considered here, the first time mark is generated upon recognition of the first format beginning (satellite time mark) following signal acquisition and receiver lock. Successive time marks are generated as follows.

(*a*) Backpack–A time mark is generated every 6,103 bits, or 2 minutes of satellite time.

(*b*) ITT 5500–Each 2-minute interval is divided into 26 subintervals. The first 25 subintervals are each 234 bits, or 4.601016 seconds, of satellite time in length. The 26th subinterval lasts for 253 bits, or 4.974603 seconds of satellite time.

(*c*) Geoceiver–Each 2-minute interval is divided into 4 subintervals as follows:

Subinterval	Number of Bits	Time Duration
1	1638	32.207111 sec.
2	1404	27.606094 sec.
3	1638	32.207111 sec.
4	1423	27.979683 sec.

Thus, in all cases, the time and duration (at the satellite) of each Doppler count is fixed and known simply from the position of the Doppler count in the format output by the receiver. Additionally, the Geoceiver outputs the reading of its local clock at the

beginning and the end of each Doppler count. From these data, the epoch error of the local clock with respect to the satellite clock may be computed. This feature also allows the computation of a small quantity known as the "partial cycle count correction." This small correction, which cannot be computed for data received by other receivers, eventually accounts for the higher precision and accuracy of the Geoceiver.

(2) The Doppler Equation. (*a*) Let t be the time of transmission from the satellite of a time mark (or a bit which will generate a time mark in the receiver). Then the counting of the beat signal begins at $t + \Delta t + \epsilon$, where Δt is the propagation delay of the signal and ϵ is a further delay composed of the time required to sense the time mark in the receiver and the wait for the next zero crossing of the beat frequency. The Doppler equation is written as

$$N = \int_{t_1 + \Delta t_1 + \epsilon_1}^{t_2 + \Delta t_2 + \epsilon_2} f_b dt \; .$$

Ignoring refraction effects (which are treated separately), Δt_1 and Δt_2 are given by r_1/c and r_2/c, where r_1 and r_2 are the ranges to the satellite at times t_1 and t_2, respectively, and c is the vacuum speed of light. The ranges are in turn given by $r_1 = \sqrt{(R_1 - x)^2}$ and $r_2 = \sqrt{(R_2 - x)^2}$ where R_1 and R_2 are the (assumed known) position vectors of the satellite (in an Earth-fixed basis) at t_1 and t_2, respectively, and x is the receiving antenna's position vector (assumed constant, but unknown).

(*b*) Substituting for f_b,

$$N = \int_{t_1 + \Delta t_1 + \epsilon_1}^{t_2 + \Delta t_2 + \epsilon_2} f_0 dt - \int_{t_1 + \Delta t_1 + \epsilon_1}^{t_2 + \Delta t_2 + \epsilon_2} f_r dt \; . \tag{1}$$

Since f_0 is constant (or at least can be considered to be so over the span of a satellite pass), the first integral is simply $f_0(t_2 - t_1 + \Delta t_2 - \Delta t_1 + \epsilon_2 - \epsilon_1)$. The second integral is more complicated. If the delay ϵ is ignored, it may be evaluated by arguing that the number of cycles received between $t_1 + \Delta t_1$ and $t_2 + \Delta t_2$ must be the same as the number of cycles transmitted between t_1 and t_2, or $f_t(t_2 - t_1)$, where f_t is the transmitted frequency. This leads to

$$\begin{aligned} N &= f_0(t_2 - t_1 + \Delta t_2 - \Delta t_1) - f_t(t_2 - t_1) \\ &= (f_0 - f_t)(t_2 - t_1) + f_0(\Delta t_2 - \Delta t_1) \end{aligned}$$

or

$$N = \Delta F \Delta T_s + f_0 (\Delta t_2 - \Delta t_1) ,$$

with

$$\Delta F = f_0 - f_1 \text{ and } \Delta T_s = t_2 - t_1 .$$

This form of the Doppler equation is often used in navigation applications. A more careful evaluation of the second integral in equation (1), considering the delay (ϵ), is given in paragraph 7. Using the result given there,

$$N = f_0 (t_2 - t_1 + \Delta t_2 - \Delta t_1 + \epsilon_2 - \epsilon_1) - f_t \left[t_2 - t_1 + \epsilon_2 - \epsilon_1 + \frac{\bar{\dot{r}}}{c} (\epsilon_2 - \epsilon_1) + \frac{1}{c} (\dot{r}_2 - \dot{r}_1) \bar{\epsilon} \right] .$$

Regrouping terms, this equation is rewritten as

$$N = \Delta F \Delta T_s + f_0 (\Delta t_2 - \Delta t_1) + \Delta F (\epsilon_2 - \epsilon_1) + \frac{\bar{\dot{r}}}{\lambda} (\epsilon_2 - \epsilon_1) + \frac{1}{\lambda} (\dot{r}_2 - \dot{r}_1) \bar{\epsilon} , \quad (2)$$

where $\Delta F = f_0 - f_t$ is the frequency offset (close to 32 kHz), $\Delta T_s = t_2 - t_1$ is the time interval at the satellite, and $\lambda = c/f_t$ is the wavelength of the transmitted signal.

(*c*) The term $f_0 (\Delta t_2 - \Delta t_1)$ contains the contribution of the Doppler shift to the count. For convenience, the term is rewritten as

$$\Delta F(\Delta t_2 - \Delta t_1) + f_t(\Delta t_2 - \Delta t_1) ,$$

or

$$\Delta F(r_2 - r_1)/c + \frac{1}{\lambda}(r_2 - r_1) .$$

The first term, $\Delta F(r_2 - r_1)/c$, is labeled C1 . In the program it is computed from approximate values of ΔF, r_2, and r_1 . The last term now shows the Doppler shift as occurring on the transmitted rather than on the reference frequency. In addition, the equation is now in a form that can be applied to GEOS satellite observations.

(*d*) The sum $\Delta F(\epsilon_2 - \epsilon_1) + \frac{1}{\lambda} \bar{\dot{r}}(\epsilon_2 - \epsilon_1)$ is labeled the PC (for partial cycle) correction. The PC term can be identified as the average beat frequency times the difference in delays at the beginning and end of the counting interval.

$$PC = (\Delta F + \frac{1}{\lambda} \bar{\dot{r}})(\epsilon_2 - \epsilon_1) = \bar{f}_b(\epsilon_2 - \epsilon_1) .$$

Although the individual delays are unknown and cannot be determined directly from the data, the difference $\epsilon_2 - \epsilon_1$ can be determined by comparing the counting interval as measured by the local clock and by the satellite clock. For Geoceiver data, this difference is computed from approximate values of r_2 and r_1, using

$$\epsilon_2 - \epsilon_1 = \Delta T_g - \Delta T_s - (r_2 - r_1)/c ,$$

where ΔT_g is the actual counting interval measured by the Geoceiver clock. The average beat frequency for the interval ΔT_s is estimated by

$$\bar{f}_b = \frac{\text{observed Doppler count}}{\Delta T_s} .$$

For data from other receivers not having a local clock, the PC term is ignored.

(*e*) The final form of the Doppler equation is thus:

$$N = \Delta F \Delta T_s + \mathrm{C1} + \frac{1}{\lambda}(r_2 - r_1) + PC + \frac{1}{\lambda}(\dot{r}_2 - \dot{r}_1)\bar{\epsilon} \quad . \tag{3}$$

b. GEOS Satellite Reception

(1) Counting Intervals. (*a*) For GEOS satellites, time marks are controlled entirely by the local clocks. Counting of the beat frequency begins at the first even 2-minute time mark (according to the local clock) following signal acquisition and receiver lock.

(*b*) The ITT 5500 simulates the bit stream from the satellite by the local generation of 6,103 bits per 2 minutes of local clock time. The subintervals within the 2-minute format are the same as for the navigation satellites.

(*c*) The Geoceiver generates a time mark every 30 seconds, on the minute and the half-minute, according to the local clock. Again, the Geoceiver also outputs the reading of the local clock at the beginning and end of each Doppler count. These times differ from even ½-minute times by the wait for the next positive-going zero crossing of the beat frequency.

(2) The Doppler Equation. Equation (2) also applies to GEOS satellite reception, except that the receiver delays do not enter into consideration. Since the interval at the satellite is not known, the Doppler equation must be written in terms of the interval measured on the ground clock. This is accomplished by rearranging equation (2) as

$$N = \Delta F \Delta T_g + \frac{1}{\lambda}(r_2 - r_1) \; . \tag{4}$$

(3) General Form. The DOPPLR program uses the following single form to include equations (3) and (4):

$$N = \Delta F \Delta T + CI + PC + \frac{1}{\lambda}(r_2 - r_1) + \frac{1}{\lambda}(\dot{r}_2 - \dot{r}_1)\bar{\epsilon} \; .$$

When navigation satellites are tracked, ΔT is ΔT_s and C1 is computed from

approximate values. When GEOS satellites are tracked, ΔT is ΔT_g and C1 = 0. The term PC is zero in all cases except for Geoceiver tracking of navigation satellites. The last term is the time bias unknown and is explained in paragraph 7. When used as the basis for the adjustment of the station location in the point positioning mode, the quantities λ, ΔT, R_1, R_2, $\dot{R}_1$, and $\dot{R}_2$ are always assumed perfectly known. The frequency offset ΔF is an unknown whose value varies from pass to pass. The station position X, as contained in the factor $(r_2 - r_1)$, is usually treated as completely unknown. However, provision is made to constrain any combination of latitude, longitude, and height to agree with input values; the degree of the constraint is determined by a priori input estimates of accuracy. The time bias unknown $\bar{\epsilon}$ may be allowed to vary from pass to pass, satellite to satellite, receiver to receiver, or it may be dropped from the equation and ignored altogether.

5. CORRECTIONS TO OBSERVED DATA. The Doppler count N of the preceding section is the ideal count, which would be obtained in the absence of physical effects on the signal. The actual measured count, d_m, is corrected to the ideal count N by

$$N = d_m - \text{corrections},$$

where the corrections are due to tropospheric and ionospheric refraction and to the relativity effect.

a. Tropospheric Refraction. (1) The correction for the tropospheric refraction (TROP) to the Doppler count is computed using the tropospheric refraction correction for each slant range. If the calculated range delay for slant range r_1 is TR_1 and for r_2 is TR_2, then

$$N + TROP = \Delta F \Delta T + \frac{1}{\lambda}(r_2 + TR_2 - r_1 - TR_1).$$

Consequently,

$$TROP = \frac{1}{\lambda}(TR_2 - TR_1).$$

TR_i is calculated by integrating the atmospheric refractivity along a line from the station to the satellite. The integral is computed for both the dry and wet components of the refractivity and the results added to give the total tropospheric delay in meters. The integral computed for each refractive component is

$$TR_i = \int_{RT + \text{lower}}^{RT + \text{upper}} \frac{N(\delta)\delta}{\sqrt{\delta^2 + RT^2 \cos^2 e}}\, d\delta, \tag{5}$$

where

δ = distance from the center of the Earth to a point on the straight line propagation path.

upper = upper limit of integration (height above station).

lower = lower limit of integration (height above station).

$\cos e$ = cosine of elevation angle.

$N(\delta)$ = refractivity at height δ.

RT = distance from Earth's center to station.

The two-quartic refractivity model developed by Hopfield[1] is used for the refractivity profile

$$N(d) = 10^{-6} * N * \frac{(\text{upper} - \text{lower} - \delta)^4}{(\text{upper} - \text{lower})^4},$$

where N is the surface refractivity.

(2) For Backpack and ITT 5500 data, the surface wet bulb (T_w) and dry bulb (T_d) temperatures and pressure (p) are measured for each pass. The surface refractivity is calculated from these values using

$$N_1 = \frac{77.62}{T_d} p .$$

$$N_2 = \left[\frac{37.19}{(T_d/100)^2} - \frac{12.92}{T_d} \right] \text{Vap} .$$

$$\text{Vap} = \text{Sat} - 0.00066(1.0 + 0.00115\, T_w)\, p\, (T_d - T_w).$$

$$\begin{aligned} \text{Sat} = {} & 0.4629 \times 10^{-10} T_w^{\ 6} + 0.155 \times 10^{-7} T_w^{\ 5} + 0.2254 \times 10^{-5} T_w^{\ 4} \\ & + 11.9792 \times 10^{-4} T_w^{\ 3} + 10.7253 \times 10^{-3} T_w^{\ 2} \\ & + 33.337 \times 10^{-2} T_w + 4.58 . \end{aligned}$$

(3) When Geoceiver observations are processed, the surface refractivity is calculated from surface temperature (T_d), pressure (p), and relative humidity (H) values.

$$N_1 = \frac{77.6}{T_d} p .$$

$$N_2 = \frac{77.6}{T_d} \left[\frac{4810}{T_d} * H * 0.01 * e^{(-37.2465 + 0.21317 T_d - 0.00026 T_d^2)} \right] .$$

The integral, equation (5), is evaluated by using the series expansion given by Yionoulis.[2]

[1] HOPFIELD, H.S. "A Two-Quartic Tropospheric Refractivity Profile for Correcting Satellite Data." Presented to the International Symposium on Electromagnetic Distance Measurement and Atmospheric Refraction, Boulder, Colorado. June 1969.

[2] YIONOULIS, S.M. "Algorithm to Compute Tropospheric Refraction Effects on Range Measurements." *Applied Physics Laboratory Technical Memorandum* TG-1125. Silver Spring, Md.: Johns Hopkins University. July 1970.

b. Ionospheric Refraction. In addition to the basic frequency from which the Doppler count is measured, both navigation and GEOS satellites transmit on a second, coherently related frequency. A comparison of the reception of the two frequencies yields a measurement of the first-order effects of ionospheric refraction. Both the Geoceiver and the ITT 5500 produce a refraction count derived from the two frequency observations. The ionospheric correction (ION) is obtained by scaling the measured refraction count. The scaling factors for the Geoceiver (Stansell, et al [3]) and the ITT 5500, are

Frequency Pair	Geoceiver	ITT 5500
400/150 MHz	6/55	24/55
324/162 MHz	1/9	8/9

In the case of the Backpack, the ionospheric correction is applied to the measured Doppler count by analog means in the receiver, so that no further correction for ionospheric refraction need be made.

c. Relativity. Because of special relativity, the frequency of the signal transmitted from the satellite appears to an observer fixed on the Earth to be lowered by a factor $(1 - v^2/c^2)^{1/2}$, where v is the velocity of the satellite in an Earth-fixed frame. This amounts to approximately 0.1 Hz at the 400 MHz frequency, or 3 counts over a 30-second counting interval. This effect is indistinguishable from a real drift of the satellite oscillator. Since the program always solves for the frequency offset (difference between transmitted and local reference frequency) on a pass-by-pass basis, it is not necessary to make a separate correction for the relativity effect. Thus, the frequency offset obtained in the solution is actually a composite of the actual frequency offset and the relativity effect.

d. Corrected Doppler Equation. The final form of the observation equation, with all known terms on the left and all unknown terms on the right, is

$$d_c = d_m - TROP - ION - C1 - PC = \Delta F \Delta T + \frac{1}{\lambda}(r_2 - r_1) + \frac{1}{\lambda}(\dot{r}_2 - \dot{r}_1)\bar{\epsilon} . \quad (6)$$

6. LOCAL CLOCK SYNCHRONIZATION. *a.* The quartz crystal oscillators used in Doppler receivers exhibit excellent short term stability, but typically drift slightly away from their intended frequency over periods of days or weeks. The receiver clock is normally started at the beginning of an operational period and allowed to run continuously for the whole operation, so that the epoch carried by the local clock typically drifts slowly away from the inital synchronization to UTC.

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[3] STANSELL, T.A., et al. "Geoceiver: An Integrated Doppler Geodetic Receiver," *Applied Physics Laboratory Technical Memorandum* TG-710. Silver Spring, Md.: Johns Hopkins University. July 1965.

b. When navigation satellites are tracked, the local clock epoch error may be determined by comparing the recorded time of the beginning of a Doppler count with the known time (in UTC) of the transmission of the corresponding bit in the navigation satellite message. If Δt_c is the correction for the local clock epoch error, t_r the time recorded by the local clock, and t the corresponding satellite (approximately UTC) time, then the UTC of the beginning of the Doppler count is

$$t_r + \Delta t_c = t + r/c + \epsilon ,$$

so that

$$\Delta t_c = t + r/c + \epsilon - t_r .$$

With the Geoceiver, a reading of the local clock t_r is obtained with each Doppler count. The reading t_r is recorded to a precision of 4 μs, the transmission time t is known to within 50 μs in UTC (the accuracy of the satellite clock in UTC), and the propagation delay r/c may be predicted to a few μs. In the program, the quantity $\Delta t_c - \epsilon$ is computed for Geoceiver observations of navigation satellites, and an average is taken over all points in the pass. Thus, the computed correction for the local clock epoch error is

$$\overline{CE} = \frac{1}{n} \sum_{i=1}^{n} (t_i + r_i/c - t_{r_i}) = \Delta t_c - \overline{\epsilon} .$$

Assuming the partial cycle wait for the zero crossing of beat frequency to be random, the average value $\overline{\epsilon}$ of ϵ may be identified as the average receiver delay. The quantity $\overline{CE}$ is computed by the program.

c. In normal field operations, the tracking of navigation satellites is the only means of determining the local clock epoch error and calibrating the drift of the local clock. Thus, navigation satellites must be tracked for timing purposes even when GEOS satellites are tracked for positioning or orbit determination purposes. When GEOS tracking data are processed by the DOPPLR program, the local clock epoch error and drift rate at a specified epoch are input and used to correct the recorded time of each data point to UTC.

7. RECEIVER DELAY. *a.* The delay ϵ is composed of the wait for the zero crossing of the beat signal and the actual receiver delay, which is the time required for a given bit in the satellite message to be recognized by the receiver logic and a signal sent to the Doppler counting circuitry. Let t be the time of transmission of a bit in the satellite message which corresponds to a time mark in the receiver. Then, the counting of the beat frequency begins at $t + r/c + \epsilon$, where r is the range at t.

b. In the receivers considered here, the delay ϵ averages approximately 1,000 μs. By contrast, the delay in the receiver of the received carrier is negligible; that is, the

delay between the time the signal is received at the antenna and the time it is mixed with the local reference frequency to produce the beat frequency is negligible (typically less than 10 μs. This means that the wave front reaching the mixer at $t + \Delta t + \epsilon$ is that which was transmitted from the satellite at $t + \Delta t + \epsilon - \Delta t'$, where $\Delta t'$ is the propagation delay of the signal arriving at $t + \Delta t + \epsilon$. Again ignoring refraction, $\Delta t'$ is $\frac{1}{c}$ times the range at $t + \Delta t + \epsilon - \Delta t'$, which is approximately $r + \dot{r}(\Delta t + \epsilon - \Delta t')$. Solving this relationship and neglecting second-order terms in $\frac{\dot{r}}{c}$ yields $\Delta t' = \Delta t + \frac{r}{c}\epsilon$, and the time of transmission is $t + \Delta t + \epsilon - \Delta t' = t + (1 - \frac{\dot{r}}{c})\epsilon$. Thus, the number of cycles received at the transmitter between $t_1 + \Delta t_1 + \epsilon_1$ and $t_2 + \Delta t_2 + \epsilon_2$ must be equal to the number transmitted between $t_1 + (1 - \dot{r}_1/c)\epsilon_1$ and $t_2 + (1 - \dot{r}_2/c)\epsilon_2$, or

$$\int_{t_1 + \Delta t_1 + \epsilon_1}^{t_2 + \Delta t_2 + \epsilon_2} f_r dt = f_t(t_2 - t_1 + \epsilon_2 - \epsilon_1 - \frac{\dot{r}_2 \epsilon_2}{c} + \frac{\dot{r}_1 \epsilon_1}{c}).$$

Since the exact delays are unknown and cannot be determined from the data, the last two terms are rewritten in terms of the mean delay $\bar{\epsilon}$, the difference in delays $(\epsilon_2 - \epsilon_1)$, and the mean range rate $\bar{\dot{r}}$ as

$$\frac{f_r}{c}(\dot{r}_2 \epsilon_2 - \dot{r}_1 \epsilon_1) = \frac{f_r}{c}\left[(\frac{\dot{r}_1 + \dot{r}_2}{2})(\epsilon_2 - \epsilon_1) + (\dot{r}_2 - \dot{r}_1)(\frac{\epsilon_1 + \epsilon_2}{2})\right]$$

$$= \frac{f_r}{c}\bar{\dot{r}}(\epsilon_2 - \epsilon_1) + \frac{f_r}{c}(\dot{r}_2 - \dot{r}_1)\bar{\epsilon},$$

therefore,

$$\int_{t_1 + \Delta t_1 + \epsilon_1}^{t_2 + \Delta t_2 + \epsilon_2} f_r dt = f_t\left[t_2 - t_1 + \epsilon_2 - \epsilon_1 + \frac{\bar{\dot{r}}}{c}(\epsilon_2 - \epsilon_1) + \frac{1}{c}(\dot{r}_2 - \dot{r}_1)\bar{\epsilon}\right].$$

c. The term $\bar{\epsilon}$ is identified as the mean receiver delay, and may, on option, be carried as an unknown by the program. However, it is indistinguishable from a constant along-track or time error in the satellite ephemeris, and may not be carried as an unknown in a problem where the satellite ephemeris is also carried as unknown. Furthermore, it is also indistinguishable from an along-track error in the receiver position. Therefore, it cannot be solved for in a navigation solution which uses only a single pass, or even in a multipass solution using only passes in a given direction. The latter situation can arise, for instance, when a receiver tracks only daytime passes of a navigation satellite for a period of several days. The restriction to only daytime passes will cause the receiver to see only the ascending (northgoing) or only the descending (southgoing) branch of the orbit.

d. When a reasonably well-balanced set of northgoing and southgoing passes is used, the mean delay $\bar{\epsilon}$ is well determined. On option, the program will solve for a separate value of $\bar{\epsilon}$ for each pass, for each satellite, or for each receiver. If the receiver delay is fairly stable, it is most reasonable to solve for a single value of this parameter for each receiver rather than for each pass. A separate solution would be made for each satellite if there were a possibility of time biases in the given satellite ephemerides. The program also allows a value for the receiver delay to be input, in which case the parameter solved for is a correction to the input value.

8. LINEARIZED OBSERVATION AND NORMAL EQUATIONS. *a.* The linearized observation equations are obtained by expanding equation (6) in a first-order Taylor series around approximate values of the unknowns ΔF (frequency offset), X (receiving antenna coordinates), and $\bar{\epsilon}$ (mean receiver delay). Thus,

$$d_c - d_c^0 = \frac{\partial d_c}{\partial \Delta F}\delta\Delta F + \frac{\partial d_c}{\partial X}\delta X + \frac{\partial d_c}{\partial \bar{\epsilon}}\delta\bar{\epsilon} \; . \tag{7}$$

In the program, the approximate value of ΔF at each iteration will be either 32 kHz (for navigation satellites) or 16.2 kHz (for GEOS satellites), although other values may be input by the user. Initial approximate values of the station coordinates are input by the user and improved at each iteration. The approximate value of the delay $\bar{\epsilon}$ is always zero on the first iteration.

b. In equation (7), d_c^0 is equation (6) evaluated with approximate values of the unknowns; $\delta\Delta F, \delta X$ and $\delta\bar{\epsilon}$ are corrections to the approximate values. The partial derivatives are

$$\frac{\partial d_c}{d\Delta F} = \Delta T \; ,$$

$$\frac{\partial d_c}{\partial X} = \frac{1}{\lambda}\frac{\partial r_2}{\partial X} - \frac{\partial r_2}{\partial X}$$

$$= -\frac{1}{\lambda}\; U_2^T - U_1^T \; ,$$

where

$$U_2 = \frac{1}{r_2}(R_2 - X),\; U_1 = \frac{1}{r_1}(R_1 - X) \; ,$$

$$\frac{\partial d_c}{\partial \bar{\epsilon}} = \frac{1}{\lambda}(\dot{r}_2 - \dot{r}_1) \; .$$

For the j^{th} observation, let

$$l_j = d_c - d_c^{o} \ ,$$

$$a_j = \frac{\partial d_c}{\partial \Delta F} \ ,$$

$$b_j = \frac{\partial d_c}{\partial \bar{\epsilon}} \ ,$$

$$c_j = \frac{\partial d_c}{\partial X} \ ,$$

Then the normal equation (for the data from a single pass) can be written as

$$\begin{bmatrix} A & A_{12} & B \\ A_{12}^T & A_2 & B_2 \\ B^T & B_2^T & C \end{bmatrix} \begin{bmatrix} \delta \Delta F \\ \delta \bar{\epsilon} \\ \delta X \end{bmatrix} = \begin{bmatrix} E \\ E_2 \\ F \end{bmatrix} ,$$

where

$$A = \sum_j a_j w_j a_j \ ,$$

$$A_{12} = \sum_j a_j w_j b_j \ ,$$

$$A_2 = \sum_j b_j w_j b_j \ ,$$

$$B = \sum_j a_j w_j c_j \ ,$$

$$B_2 = \sum_j b_j w_j c_j \ ,$$

$$C = \sum_j c_j^T w_j c_j \ ,$$

$$E = \sum_j a_j w_j l_j \ ,$$

$$E_2 = \sum_j b_j w_j l_j \ ,$$

$$F_2 = \sum_j c_j^T w_j l_j \ .$$

The summation is taken over all the observations during the pass. The weights, w_j, are equal to either unity or to the reciprocal of the square of the input observational standard derivation. In addition, the quantity

$$D = \Sigma_j l_j w_j l_j$$

is useful for statistical computations. In the program, subroutine NORST generates all

these quantities for each pass. Subroutine NORSE is similar but omits the calculation of b_j and the matrices A_2, A_{12}, B_2, and E_2.

c. The three subroutines, STASTA, STASOT, and STASOL, combine the matrices from all the passes. They perform very similar series of matrix manipulations designed for a system of normal equations which, when partitioned, take the form

$$\begin{bmatrix} G_1 & . & . & . & & H_1 \\ . & G_2 & & & & H_2 \\ . & & . & & & . \\ & & & & & \\ & & & . & & . \\ & & & & G_N & H_N \\ H_1^T & H_2^T & . & . & H_N^T & Q \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ . \\ \\ . \\ Y_N \\ Z \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ . \\ \\ . \\ P_N \\ R \end{bmatrix} \tag{8}$$

In each case Y_k refers to the pass unknowns.

In STASTA:

Y_k = $\delta \Delta F$ for the k^{th} pass,
Z = δX plus a $\delta \bar{\epsilon}$ for each satellite (receiver),
G_k = A for the k^{th} pass,
H_k = an array made up of A_{12} and B for the k^{th} pass,
P_k = E for the k^{th} pass,
Q = the summation (over all passes of A_2, B_2, B_2^T, and C, appropriately arranged by satellite [receiver]),
R = the summation (over all passes of E_2 and F, appropriately arranged by satellite [receiver]).

In STASOT:

Y_k = $\delta \Delta F$ and $\delta \bar{\epsilon}$ for the k^{th} pass,
Z = δX,

$$G_k = \begin{bmatrix} A & A_{12} \\ A_{12} & A_2 \end{bmatrix} \text{for the } k^{th} \text{ pass,}$$

$$H_k = \begin{bmatrix} B \\ B_2 \end{bmatrix} \text{ for the } k^{th} \text{ pass,}$$

$$P_k = \begin{bmatrix} E \\ E_2 \end{bmatrix} \text{ for the } k^{th} \text{ pass,}$$

$Q \quad = \quad \Sigma C$ where the summation is over all passes,

$R \quad = \quad \Sigma F$ where the summation is over all passes.

In STASOL:

$Y_k \quad = \quad \delta \Delta F$ for the k^{th} pass,

$Z \quad = \quad \delta X$,

$G_k \quad = \quad A$ for the k^{th} pass,

$H_k \quad = \quad B$ for the k^{th} pass,

$P_k \quad = \quad E$ for the k^{th} pass,

$Q \quad = \quad \Sigma C$ summation over all passes,

$R \quad = \quad \Sigma F$ summation over all passes.

Also let

$V \quad = \quad \Sigma D$ summation over all passes.

With a system of equations in the form of equation (8), Y_k can be eliminated to give

$$(Q - \Sigma H_k^T G_k^{-1} H_k) Z = R - \Sigma H_k^T G_k^{-1} P_k \ ,$$

so that the solution for Z is

$$Z = (Q - \Sigma H_k^T G_k^{-1} H_k)^{-1} (R - \Sigma H_k^T G_k^{-1} P_k) \ .$$

Also, the sum of the squares of the residuals is given by

$$V - \Sigma P_k^T G_k^{-1} P_k - (R - \Sigma H_k^T G_k^{-1} P_k)^T (Q - \Sigma H_k^T G_k^{-1} H_k)^{-1} (R - \Sigma H_k^T G_k^{-1} P_k)$$

from which their root mean square (rms) can be calculated. This, together with the inverse of the normal equations

$$(Q - \Sigma H_k^T G_k^{-1} H_k)^{-1}$$

corresponding to Z, forms the basis for calculating the error statistics for Z .

Y_k is calculated from

$$Y_k = G_k^{-1} P_k - G_k^{-1} H_k Z \ ,$$

and the inverse of the normal equations corresponding to Y_k is

$$G_k^{-1} + G_k^{-1} H_k (Q - \Sigma H_k^T G_k^{-1} H_k)^{-1} (G_k^{-1} H_k)^T \ .$$

This, with the rms, gives the basis for calculating the errors of Y_k .

9. WEIGHT MATRIX FOR OBSERVATION EQUATIONS. *a.* Normally, each observation is weighted inversely proportional to the variance of the range difference observation. This variance is defined in an input array and is assumed equal for all observations. It is also assumed that the range difference observations are independent, having a random error with zero mean and constant (but unknown) standard deviation. It is possible within the program to treat range as the independent uncorrelated variable rather than range difference. This is accomplished by redefining the weight matrix.

b. Assume the range observation equation can be written as

$$r_i = r_o + f_i(P),$$

where r_o is the zero set (initial range) and P are other parameters. Further assume that ranges (r_i) are all independent with equal uncertainties, σ .

Then

$$r_i - r_{i-1} = f_i(P) - f_{i-1}(P)$$

and

$$\begin{bmatrix} r_2 - r_1 \\ r_3 - r_2 \\ \cdot \\ \cdot \\ \cdot \\ r_m - r_{m-1} \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & \cdot & \cdot & \cdot & 0 & 0 \\ 0 & -1 & 1 & & & & 0 & 0 \\ \cdot & & & \cdot & & & & \cdot \\ \cdot & & & & \cdot & & & \cdot \\ \cdot & & & & & \cdot & & \cdot \\ 0 & 0 & 0 & \cdot & \cdot & \cdot & -1 & 1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ \cdot \\ \cdot \\ \cdot \\ r_{m-1} \\ r_m \end{bmatrix}$$

The covariance matrix of $\{r_2 - r_1, r_3 - r_2, \ldots r_m - r_{m-1}\}$ is then

$$\begin{bmatrix} -1 & 1 & 0 & \ldots & 0 & 0 \\ 0 & -1 & 1 & & 0 & 0 \\ \cdot & & \cdot & & & \cdot \\ & & & & & \\ 0 & 0 & 0 & \ldots & -1 & 1 \end{bmatrix} \begin{bmatrix} \sigma^2 & 0 & \ldots & 0 \\ 0 & \sigma^2 & & 0 \\ \cdot & & \cdot & \cdot \\ & & & \\ 0 & 0 & \ldots & \sigma^2 \end{bmatrix} \begin{bmatrix} -1 & 0 & \ldots & 0 & 0 \\ 1 & -1 & & 0 & 0 \\ \cdot & & \cdot & & \cdot \\ \cdot & & & \cdot & \cdot \\ 0 & 0 & & -1 & 0 \\ 0 & 0 & \ldots & 1 & -1 \end{bmatrix}$$

$$= \sigma^2 \begin{bmatrix} 2 & -1 & \ldots & 0 & 0 \\ -1 & 2 & & 0 & 0 \\ \cdot & & \cdot & & \cdot \\ \cdot & & \cdot & & \cdot \\ 0 & 0 & & 2 & -1 \\ 0 & 0 & \ldots & 1 & 2 \end{bmatrix} = \Sigma\Delta .$$

The appropriate weight matrix is then Σ_{Δ}^{-1} and this can be calculated using

$$(\Sigma_{\Delta}^{-1})i,j = \begin{array}{l} i(m+1-j)/(m+1)\sigma^2 \text{ for } j \geqslant i \\ j(m+1-i)/(m+1)\sigma^2 \text{ for } i \geqslant j \end{array} .$$

The introduction of this weight equation allows the integrated Doppler observations to be treated as if they were equivalent to range observations.

10. ERROR ANALYSIS CAPABILITY. An error analysis capability has been included in DOPPLR. This capability permits the investigation of the effects of unestimated errors on estimated parameters in the Doppler solutions. The effects of biases and random errors are calculated as perturbations to either observed or perfect Doppler counts and solutions performed using the perturbed data.

11. CALPRT ROUTINE. The routine (CALPRT) calculates perturbations to the observed Doppler counts. Acceptable error source parameters are defined as follows.

a. Observation—An error in the corrected integrated Doppler count. This includes digitizing, receiver phase shifts, and refraction truncation errors.

b. Timing—An error in the time recovery within the receiver due to varying signal-to-noise ratio. This is calculated for each time mark.

c. Offset Frequency—An error in the assumed frequency difference between the fundamental satellite transmission frequency and the local oscillator frequency.

d. Satellite Frequency—An error due to an incorrect satellite transmission frequency.

e. Troposphere—An error resulting from the limitation of the tropospheric model. This is calculated as a percentage error of the modeled tropospheric correction.

f. Ionosphere—An error due to neglecting higher-order terms in using the two-frequency technique. This error is modeled as a percentage of the measured two-frequency ionospheric correction.

g. Ephemeris—An error due to the uncertainty in the position of the satellite at the time of observation. The error is subdivided into radial, along-track, and crosstrack components.

The perturbation, Δd_m , for each error parameter, P_i , is calculated using

$$\Delta d_m = \frac{\partial d_c}{\partial P_i} \Delta P_i ,$$

where

d_c = basic integrated Doppler observation equation and
ΔP_i = the magnitude of the error parameter.

The calculated perturbation may be combined with the Doppler counts as a bias, as a random perturbation per Doppler count, or as a bias per pass but random between passes. The options available for each parameter are shown in table 1.

Table 1. Parameter Options

PARAMETER	BIAS	σ/POINT	σ/PASS
Observation	X	X	
Timing	X	X	X
Offset Frequency	X	X	
Satellite Frequency	X	X	
Troposphere (%)	X		X
Ionosphere (%)	X		X
Ephemeris			
Radial	X	X	X
Crosstrack	X	X	X
Along Track	X	X	X

SECTION III. PROGRAM OPERATION

12. GENERAL RUN STRUCTURE. The data deck necessary for a Doppler solution is built from the initializing constants deck, the pass observation deck, and the system control cards as shown schematically in figure 1. It is possible to do more than one Doppler solution at a time by stacking decks similar to the single solution deck as shown in figure 2, and multiple solutions using different options with the same set of data can be accomplished as shown in figure 3.

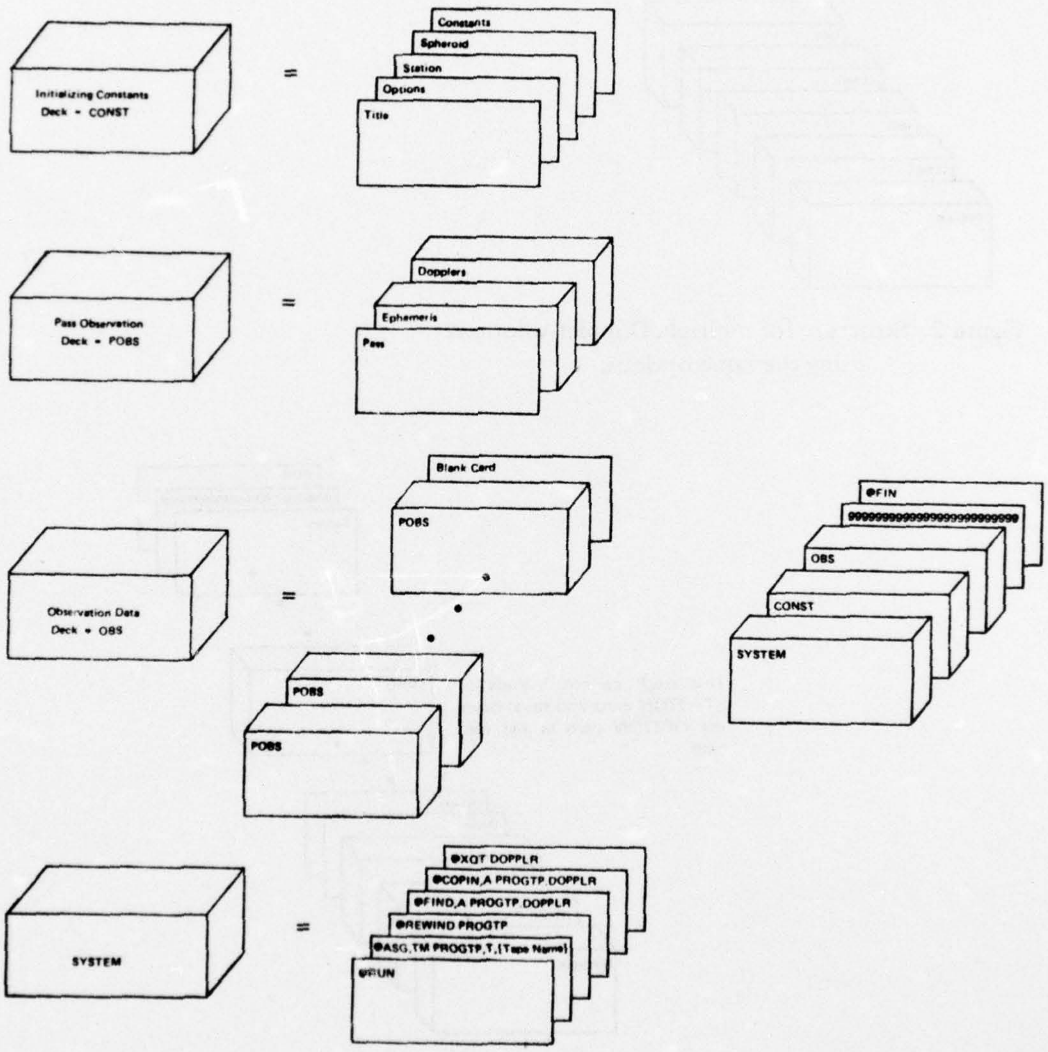

Figure 1. Single Doppler solution data deck structure.

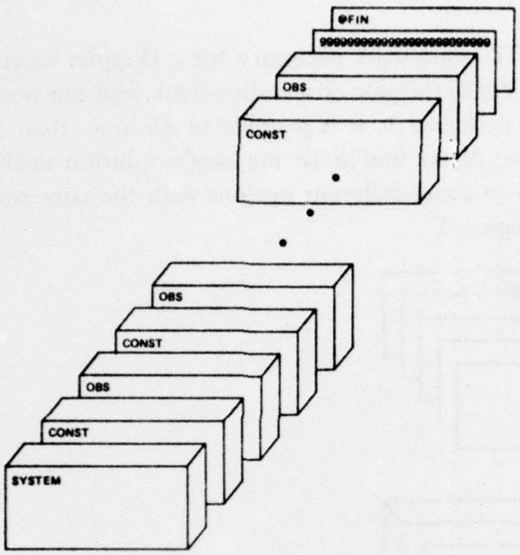

Figure 2. Structure for multiple Doppler solutions using the same options.

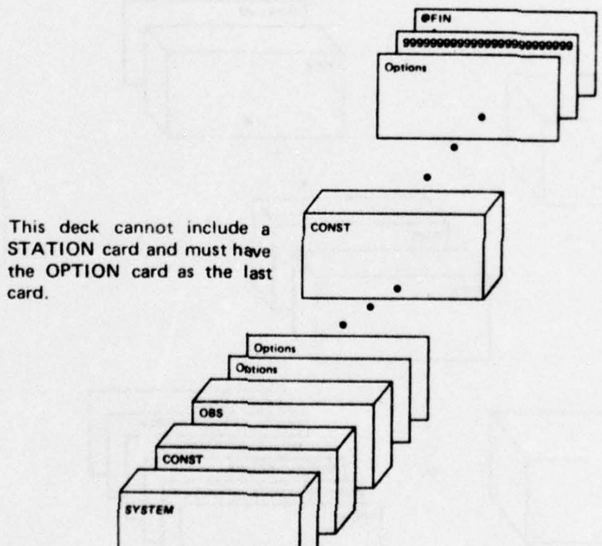

Figure 3. Structure for multiple Doppler solutions using different options.

13. INITIALIZING CONSTANTS DECK. *a.* The initializing constants which can be specified for a solution include any of the following: station coordinates, spheroid parameters, datum shifts, velocity of light, station receiver delay, satellite frequency offset, satellite transmitting wavelength, title, and various program control options. The input of any of these values is identified by the appropriate word left-justified on the input card. Table 2 lists the acceptable card formats to be included in the deck of constants. These inputs form the initializing constants deck and may appear within this deck in any order. If more than one card appears with the same identification left-justified on the card, the last definition overrides previous definitions.

b. Input of the perturbations to be included in an error analysis run can also be included in the initializing constants deck. This input requires two or more cards in sequence; these cards, however, may be in any order with respect to the other input in the initializing constants deck. The perturbations are read as a NAMELIST and, therefore, obey all FORTRAN V rules pertaining to NAMELISTS. In addition, one header card must be included in the NAMELIST and all numerical input must be expressed as double precision. Table 3 gives acceptable parameters in the NAMELIST. Values for any or all of these parameters may be specified in any NAMELIST definition. The random perturbations are normally applied per observation; however, if the value for the random error parameter is negative, the perturbation is applied as a bias per pass but random between passes. The card formats for entering perturbation data are shown in table 4.

c. In computing a solution with real data, it is only necessary to input the OPTION and STATION cards, provided the station is input on the NWL 8D datum. If the station is input on another datum specified by column 80 on the STATION card, a SPHEROID card defining the datum shifts to the geocentric NWL 8D datum is also required. If not input, the following constants are preset to the indicated values:

Title = solution for xxxxxx, where xxxxxx is the station name,

Velocity of Light = 299 792 500.0 meters per second (m/sec),

Satellite λ = 0.74954121 m (400–150 MHz Mode),

Offset Frequency = 32,000 Hz,

Spheroid Name = 3H NWL,

A0 = 6 378 145.0 m,

Flattening = 0.003352892,

Dry Component of Surface Refractivity = 292.9,

Wet Component of Surface Refractivity = 75.6.

Table 2. Deck of Constants Card Formats

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
TITLE	5H TITLE	1–5	A6
CARD	70-Character Title	10–80	11A6,A4
STATION	7H STATION	1–7	A6
CARD	Station Name	10–15	A6
	= 0 for ϕ, λ, h input (degrees, degrees, meters) = 1 for x, y, z input (meters, meters, meters)	17	I1
	Station Code (as defined on the pass ID)	18	A1
	Station ϕ or x	20–34	D15.3
	λ or y	35–49	D15.3
	h or z (where h is the total height of the antenna above the ellipsoid)	50–64	D15.3
	Geoid Separation (meters)–used only in the computation of the tropospheric correction	65–79	D15.3
	Datum Code–matches the first character of the datum named on the SPHEROID card	80	A1
SPHEROID	8H SPHEROID	1–8	A6
CARD	Datum Name–first character of this name matches datum code on the STATION card	10–15	A6
	Semimajor Axis (meters)	20–34	D15.3
	Ellipsoid Flattening	35–49	D15.3
	Datum Shift (Geocentric coordinates of origin of system defined on this card)		
	x component (meters)	50–59	D10.3
	y component (meters)	60–69	D10.3
	z component (meters)	70–79	D10.3
CONSTANT	9H CONSTANTS	1–9	A6
CARD	Velocity of Light (meters/sec)	20–34	D15.5
	Receiver Delay (μs)	35–49	D15.5
	Frequency Offset (Hz)	50–64	D15.5
	Satellite Wavelength (meters)	65–79	D15.5

Table 2. Deck of Constants Card Formats—Continued

CARD NAME	OPTION NO.	PARAMETER	Punch Code yes	Punch Code no	CARD COLUMN	FORMAT
OPTION CARD		6H OPTION			1–7	A6
	1	Number of Iterations			10	I1
	2	Print residuals on last iteration only	1	0	11	I1
	3	Print Residuals	0	1	12	I1
	4	Plot Residuals	1	0	13	I1
	5	Observation Sigma (meters) Preset to 0.75m if not input			14–17	I4
	6	Station Latitude Sigma (meters)			18–21	I4
	7	Station Longitude Sigma (meters)			22–25	I4
	8	Station Height Sigma (meters)			26–29	I4
	9	Plot station positions obtained from single pass solutions	1	0	30	I1
	10	Apply tropospheric correction	0	1	31	I1
	11	Do single-pass navigation solutions	0	1	32	I1
	12	Data Source = 0 use real data = 2 use data from previous run with original station input as on STATION card = 3 use data from previous run with station position from last solution = 9 Stop			33	I1
	13	Local Time and Satellite Track Plots >1 Print distribution of passes in local time = 1 also plot subsatellite points = 0 do neither of above			46	I1
	14	Perform solution without time bias adjustment	0	1	47	I1
	15	Delete samples with elevation angles less than this value (degrees)			48–49	I2

Table 2. Deck of Constants Card Formats—Continued

CARD NAME	OPTION NO.	PARAMETER	Punch Code yes	Punch Code no	CARD COLUMN	FORMAT
	16	Local Time Deletion of Passes				
		= 0 no deletion on local time			50–51	I2
		= *xx* and				
		= *yy* keep those with *xx*<local time<*yy*			52–53	I2
	17	rms multiple for residual editing			54	I1
	18	North–South Pass Deletion			55	I1
		= 0 use all passes				
		= 1 use only north-going passes				
		= 2 use only south-going passes				
	19	Equipment Delay Adjustment			56	I1
		= 1 adjust $\bar{\epsilon}$ varying pass to pass				
		= 2 satellite to satellite				
		= 3 receiver to receiver				
	20	Apply ionospheric correction	0	1	57	I1
	21	Fix frequency offset for single-pass solution plots to values from previous solution	2	0	58	I1
	22	Deletion multiple for single-pass solution plots			59	I1
	23	Data Type			60	I1
		= 0 ITT Doppler data (P, T, R)				
		= 1 Quick-check data				
		= 2 Backpack data				
		= 3 Geoceiver data				
		= 4 ITT Doppler data (P, T_w, T_d)				
	24	Timing Mode			61	I1
		= 0 satellite clock				
		= 1 local clock				
	25	Generate Perfect Data	9	0	62	I1
	26	Weight Matrix			63	I1
		= 0 range difference formulation				
		= 1 range formulation				

Table 3. NAMELIST Parameters

ERROR SOURCE	ACCEPTABLE PARAMETER NAMES BIAS	RANDOM ERROR
Observation	OBIAS	OBSIG
Timing	TIMEB	TIMSIG
Offset Frequency	FBIAS	FSIG
Satellite Frequency	---	TFSIG
Tropospheric	TROPOZ	---
Ionospheric	IONOZ	---
Ephemeris		
Radial	RADIAL	SIGRAD
Crosstrack	CROSS	SIGCRS
Along Track	ALONG	SIGALG

Table 4. Perturbation Data Card Format

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
CARD 1	5H $PERT	1–5	A5
CARD 2	5H $PERT	1–5	A5
⋮	⋮		
CARD N	4H $END	1–4	A4

14. OBSERVATION DATA DECK. The observation data deck for each pass consists of a pass identification (ID) card, ephemeris cards, and Doppler cards (figure 4).

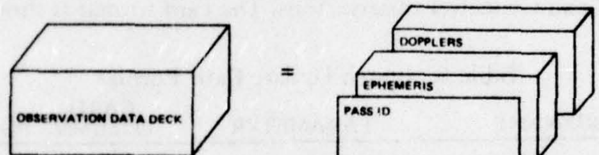

Figure 4. Observation data deck structure.

a. Pass Identification Card. The pass ID card is the first card for each pass and must follow the format shown in table 5. The quantities in columns 1–26 are required inputs. If the wet and dry bulb temperatures and pressure are not specified, they are set to standard values. On the pass ID card, if either of the values for frequency offset or satellite wavelength is zero, preset values or values from the constants deck are used.

Table 5. Pass Identification Card Format

CARD NAME	PARAMETER		CARD COLUMN	FORMAT
PASS ID	4H PASS		1–4	A4
	Pass Number		5–10	A6
	Satellite Identification		11	A1
	Station Identification		12	A1
	Month of Pass		14–15	I2
	Day of Pass (GMT)		16–17	I2
	Year of Pass		18–19	I2
	Hour of Pass (GMT)		23–24	I2
	Minute of Pass (GMT)		25–26	I2
	Mode (Geoceiver input only)		28	I2
	Dry Bulb Temperature (°F)	For observation types 0, 1, and 2	31–40	D10.2
	Wet Bulb Temperature (°F)	For observation types 0, 1, and 2	41–50	D10.2
	Pressure (mm/Hg)	For observation types 0, 1, and 2	51–60	D10.2
	Dry Bulb Temperature (°C)	For observation types 3 and 4	31–40	D10.2
	Relative Humidity (%)	For observation types 3 and 4	41–50	D10.2
	Pressure (mb)	For observation types 3 and 4	51–60	D10.2
	Frequency Offset (Hz) for pass		61–70	D10.2
	Satellite Wavelength (m) for pass		71–80	D10.2

b. Clock Epoch Update Card. The epoch update card permits a local clock epoch error, drift rate, and scale factor to be introduced in the preprocessor. This card, if used, follows the pass ID card and all subsequent observational times are corrected using this information until another epoch update is encountered. This input can only be used with ITT and Geoceiver observations. The card format is shown in table 6.

Table 6. Epoch Update Card Format

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
EPOCH UPDATE CARD	6H TIME	1–4	A4
	DAYS since Jan 0	10–12	I3
	Hours	15–16	I2
	Minutes	18–19	I2
	Epoch Delay (μs)	25–39	D15.10
	Drift Rate (μs/day)	45–59	D15.10
	Scale Factor	65–79	D15.10

c. *Ephemeris Card Input.* The satellite ephemeris for each pass can be input to the processor in any of the three following formats:

- As discrete satellite ephemeral points at a fixed time interval.

- As coefficients for Chebychev polynomials which describe the fixed-Earth x, y, and z variation of the satellite with time. These are produced by the separate program COPYTP from an ephemeris on magnetic tape.

- As satellite message words received from the navigation satellite (predicted ephemeris).

(1) Ephemeris Point Input. If the ephemeris is input as discrete satellite points, the structure of the ephemeris deck follows the format shown in table 7. Following card 1, the satellite points are input one per card, as indicated. The card for the last ephemeral point must have a "1" in the first column to signify the end of the ephemeris input. The time for each ephemeris point must increase by N2 minutes

Table 7. Ephemeris Card Format (Discrete Satellite Points)

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
CARD 1	6H POINTS	1–6	A6
	4H PASS	21–24	
	Orbit Number	27–32	A6
	Satellite Identification	33	A1
EPHEMERIS POINT CARD	Termination Indicator = 0 normally = 1 last ephemeral point	1	I1
	Month of Ephemeral Point (GMT)	9–10	I2
	Day of Ephemeral Point (GMT)	11–12	I2
	Year of Ephemeral Point (GMT)	13–14	I2
	Hour of Ephemeral Point (GMT)	16–17	I2
	Minute of Ephemeral Point (GMT)	18–19	I2
	Fixed Earth Ephemeral Position and Velocity		
	x (meters)	21–30	F10.3
	y (meters)	31–40	F10.3
	z (meters)	41–50	F10.3
	$\dot{x}$ (meters/sec)	51–60	F10.3
	$\dot{y}$ (meters/sec)	61–70	F10.3
	$\dot{z}$ (meters/sec)	71–80	F10.3

over the preceding point. N2 is a parameter preset to 2 minutes (preprocessors PROC or OBSIN) and corresponds to the integration interval over which the Doppler counts are measured. A missing ephemeris point will cause the entire pass to be deleted. The maximum number of ephemeris points which can be entered for a particular pass is controlled by parameter N1 which is preset to 11. An example of the input card deck for the ephemeris points is shown in figure 5. These points are for pass 13504 of satellite Y on 23 June 1970. The first ephemeral point is at 05 hours 16 minutes and the last at 05 hours 36 minutes.

(2) Ephemeris Coefficient Input. The segment of the ephemeris over which observations have been made can be fit with Chebychev polynomials of the form

$$f_x(x) = \sum_{n=0}^{6} \sum_{m=0}^{n} (-1) \begin{bmatrix} n \\ m \end{bmatrix} \begin{bmatrix} n+m \\ m \end{bmatrix} \frac{x!(N-m)!}{(x-m)!N!} A_{xn} ,$$

where the observation interval has been divided into N equal segments so that x takes the values (0, 1, 2, ..., N). The coefficients A_n can then be input to the processor, thus reducing the input needed to specify an ephemeris arc. The formats for the ephemeris deck cards with Chebychev coefficients are shown in table 8.

An example of this ephemeris input for pass 13504 is shown in figure 6. From these coefficients the actual ephemeral points can be evaluated by the following formula:

Actual Time	Parameter t
05 hr 16 min	$t = 0$
05 hr 18 min	1
⋮	⋮
05 hr 36 min	11

$$x(t) = \sum_{n=0}^{6} A_{xn} f_n(t) ,$$

$$y(t) = \sum_{n=0}^{6} A_{yn} f_n(t) ;$$

$$z(t) = \sum_{n=0}^{6} A_{zn} f_n(t) ,$$

where

$$f_n(t) = \sum_{m=0}^{n} (-1)^m \begin{bmatrix} n \\ m \end{bmatrix} \begin{bmatrix} n+m \\ m \end{bmatrix} \frac{t!(N-m)!}{(t-m)!N!} .$$

```
POINTS               PASS    13504Y
0       62370   516    3936047.0-5054950.0 3750615.0 1991.1690-3137.3870-6342.8960
0       62370   518    4145910.9-5397243.0 2964908.0 1470.8070-2559.2350-6736.9320
0       62370   520    4288621.9-5667345.9 2137528.0  939.9890-1935.5950-7036.6020
0       62370   522    4369420.0-5860314.9 1280078.0  406.9620-1275.2070-7257.4540
0       62370   524    4386530.9-5972301.9  404613.0 -120.1210 -587.5110-7356.5640
0       62370   526    4341146.0-6000625.0 -476350.0 -653.3400  117.4920-7352.2850
0       62370   528    4235387.0-5943827.0-1351007.0-1125.1460  829.4080-7224.8900
0       62370   530    4072251.0-5801715.0-2206460.0-1568.4870 1537.6320-7015.9700
0       62370   532    3855546.0-5575368.0-3030903.0-2016.9360 2231.5480-6708.6970
0       62370   534    3589811.0-5267134.0-3812796.0-2404.7870 2900.6940-6307.6890
1       62370   536    3280219.0-4880598.0-4541237.0-2747.1410 3534.9460-5818.9510
```

Figure 5. Listing for ephemeris points input.

```
COEFFICIENTS       PASS   13504Y    POINTS 11      DEGREE  6      TIME  2
X       0516 4045353.7  342738.6 -439800.6  -14083.5   2583.2        58.8        -3.3
Y       0516-5583765.7  -82445.7  619699.7   -4754.8  -3712.8        24.5         4.9
Z       0516 -443746.5 4218360.0   48742.2  -72623.8   -307.3       183.3         0.5
```

Figure 6. Listing for ephemeris coefficients input.

The coefficients shown in figure 6 were computed by the ephemeris preprocessor from the 11 points indicated for this pass in figure 5. These points are obtained from the ephemeris tape by the ephemeris preprocessor, which searches the ephemeris tape and either extracts the discrete points or computes the coefficients and outputs the ephemeral segment on punched cards with the formats shown.

Table 8. Ephemeris Card Format (Chebychev Coefficients)

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
CARD 1	12H COEFFICIENTS	1–12	A6
	4H PASS	18–21	––
	Orbit Number	23–28	A6
	Satellite Identification	29	A1
	6H POINTS	33–38	––
	Number of points used in Chebychev polynomial fit for each component f_x, f_y, and f_z	40–41	I2
	6H DEGREE	47–52	––
	Degree of Polynomial Fit	55	––
	4H TIME	61–64	––
	Time interval in minutes between satellite points used in polynomial fit	66–67	I2
CARDS 2–4	1HX or 1HY or 1HZ corresponding to input of the polynomial coefficient for the x component, y component, or z component of the ephemeral arc	1	A1
	Hour of first point used in polynomial fit which corresponds to ($x = 0$) (GMT)	7–8	I2
	Minute of first point (GMT)	9–10	I2
	A_{x0}	11–20	D10.4
	A_{x1}	21–30	D10.4
	A_{x2}	31–40	D10.4
	A_{x3}	41–50	D10.4
	A_{x4}	51–60	D10.4
	A_{x5}	61–70	D10.4
	A_{x6}	71–80	D10.4

(3) Satellite Message Ephemeris Input. The third form of ephemeral input is the satellite message ephemeris as received from NNS. The satellite message consists of both fixed parameters and variable parameters; a complete description of these parameters can be found in Gutheim. [4] Table 9 gives the card format for the satellite message ephemeris input. The parameters entered on cards 2 through 5 are exactly as received; the fixed parameters are decoded in the Doppler processor into orbital elements and the variable parameters into 2-minute corrections to the orbital parameters. The number of variable parameters entered on cards 2 and 3 is determined by the timespan of the observations for the particular pass. The first variable parameter must precede the time of the first observation and the last variable parameter must be later than the last observation time. If less than nine variable parameters are input, a blank card must be used for card 3.

d. Doppler Input Deck. Three different formats can be used for the input of the integrated Doppler observations. The type of Doppler input is specified in the option card (column 60) and must be one of the following:

- Geoceiver
- ITT 5500
- Backpack.

Within a solution deck, the Doppler counts must be of a single type; however, in multiple processing runs, the Doppler data type may differ between successive solution decks.

(1) Geoceiver Doppler Input. A Geoceiver observation consists of a time indicating the start of the counting interval, the duration time of the count, the Doppler count, and the refraction count. Two observations may be put on a single card in the format shown in table 10. The Doppler deck consists of observation cards only. The time sequence of the observations on the cards or within the deck is not important in the program execution but may, however, result in a difference in internal storage requirements. Internal program parameters limit the number of ephemeris points to 35 per pass and these points are controlled by both the number of Doppler counts input and their time sequence.

(2) ITT 5500 Doppler Input. The input of ITT 5500 integrated Doppler observations is identical to the Geoceiver input except that the input of seconds for the starting time and duration time is replaced by line counts. One line count is equal to (234/6103) * 120 seconds. This simplifies the input of the ITT Doppler counts since this unit outputs a Doppler count and refraction count every 4.6010159 seconds as it is accumulating the full 2-minute count. A special symbol, "P," which is used in the column following the duration line count, indicates that an interval of 0.3735868 seconds has been included in the observation duration (i.e., 26 lines + 0.3735868 seconds = 120.0 seconds). The format for input of ITT observations appears in table 11.

[4] GUTHEIM, G.C. "Program Requirements for Two-Minute Integrated Doppler Satellite Navigation Solution." *Applied Physics Laboratory Technical Memorandum* TG 819-1. Silver Spring, Md.: Johns Hopkins University. April 1967.

Table 9. Satellite Message Card Format

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
CARD 1	9H SATELLITE	1–9	A6
	Orbit Number	21–26	——
	Satellite Identification	27	——
CARD 2	Variable Parameter		
	1	1–10	I10
	2	11–20	I10
	3	21–30	I10
	4	31–40	I10
	5	41–50	I10
	6	51–60	I10
	7	61–70	I10
	8	71–80	I10
CARD 3	Variable Parameter		
	9	1–10	I10
	10	11–20	I10
	11	21–30	I10
	12	31–40	I10
	13	41–50	I10
	14	51–60	I10
	15	61–70	I10
	16	71–80	I10
CARD 4	Fixed Parameter Inputs		
	Time of Perigee t_p	1–10	I10
	Mean Motion N	11–20	I10
	Argument of Perigee at t_p	21–30	I10
	Precession Rate of Perigee	31–40	I10
	Eccentricity	41–50	I10
	Mean Semimajor Axis	51–60	I10
	Right Ascension of Ascending Node at t_p	61–70	I10
	Precession Rate of Node	71–80	I10
CARD 5	Fixed Parameter Inputs		
	Cosine of Inclination	1–10	I10
	Longitude of Greenwich at t_p	11–20	I10
	Time of Last Satellite Injection	21–30	I10
	Sine of Inclination	41–50	I10
	Frequency Offset in ppm	51–60	I10

Table 10. Doppler Card Format (Geoceiver)

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
OBSERVATION CARD	Orbit Number	1–6	A6
	Satellite Identification	7	A1
	Station Identification	8	A1
	Starting Time (GMT) for Observation 1		
	Hour	10–11	I2
	Minutes	12–13	I2
	Seconds	14–19	F6.4
	Counting Duration		
	Minutes	20–21	I2
	Seconds	22–30	F9.6
	Doppler Count (decimal)	31–38	I8
	Refraction Count (decimal + 2000)	39–43	I5
	Starting Time (GMT) for Observation 2		
	Hour	45–46	I2
	Minutes	47–48	I2
	Seconds	49–54	F6.4
	Counting Duration		
	Minutes	55–56	I2
	Seconds	57–65	F9.6
	Doppler Count (decimal)	66–73	I8
	Refraction Count (decimal + 2000)	74–78	I5

(3) Backpack Doppler Input. The Doppler preprocessor for the Backpack data (PROC) requires only an estimate of the starting time of the first Doppler count in order to match the Doppler counts to the correct satellite 2-minute interval. All the Doppler counts must be of 2-minute duration and must be corrected for ionospheric refraction. Table 12 gives the input format. The program parameters are set to allow two Doppler cards at most or eight 2-minute Doppler observations; however, for four or less observations only one card need be input.

15. OUTPUT DESCRIPTION. The output from the DOPPLR program is controlled by the options specified on the OPTION card in the initializing constants deck. On initial entry into the program, all input data are read and a data file is created by the preprocessor. During this process, the output shown in figure 7 is generated. The initializing constants for the particular run are output along with a pass-by-pass summary of the data and associated corrections. Following the generation of the data file, the specific data processing options on the OPTION card are executed in sequence. A description of each of the data processing options and the associated output generated by the options are as follows.

Table 11. Doppler Card Format (ITT)

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
OBSERVATION CARD	Orbit Number	1–6	A6
	Satellite Identification	7	A1
	Station Identification	8	A1
	Starting Time (GMT) for Observation 1		
	Hour	10–11	I2
	Minutes	12–13	I2
	Line Counts	14–15	I2
	Counting Duration		
	Minutes	20–21	I2
	Line Counts	22–23	I2
	Special Interval Symbol "P"	24	A1
	Doppler Count	31–38	I8
	Refraction Count	39–43	I5
	Starting Time (GMT) for Observation 2		
	Hour	45–46	I2
	Minutes	47–48	I2
	Line Counts	49–50	I2
	Counting Duration		
	Minutes	55–56	I2
	Line Counts	57–58	I2
	Special Interval Symbol "P"	59	A1
	Doppler Count	66–73	I8
	Refraction Count	74–78	I5

a. *OPTION 9–Plot Station Positions Obtained From Single-Pass Solutions.* Three single-pass navigation solutions are performed constraining the station height, longitude, and latitude, respectively, for each pass. The resulting change in station position referenced to the input coordinate is output as shown in figure 8. Plots (figures 9, 10, and 11) are also generated for each of the three different constraint conditions showing the distribution of the navigation solutions for each pass. A deletion rms multiplier (OPTION 22) can be input so that extreme navigation values will not be plotted. In addition, if a combined solution was performed prior to the navigation, OPTION 21 will also constrain the value of the frequency offset for each pass used in the navigations to that of the multipass solution.

b. *OPTION 11–Do Single-Pass Navigation Solutions.* Single-pass navigation solutions are computed in the plane defined by the satellite positions corresponding to the first and last observation and the input station position. The two components of the

Table 12. Doppler Card Format (Backpack)

CARD NAME	PARAMETER		CARD COLUMN	FORMAT
OBSERVATION CARD	Orbit Number		1–6	A6
	Satellite Identification		7	A1
	Station Identification		8	A1
	Station Name		9–14	A6
	Doppler Type Code		18	I1
	= 1 Data = Obs			
	= 2 Data = Obs			
	Observation			
	1	For data type 2	20–30	011
	2	For data type 2	35–45	011
	3	For data type 2	50–60	011
	4	For data type 2	65–75	011
	Observation			
	1	For data type 1	24–30	I7
	2	For data type 1	39–45	I7
	3	For data type 1	54–60	I7
	4	For data type 1	69–75	I7

station position in this plane and a frequency offset are estimated for each navigation solution. A total of three iterations are performed with residual editing based on the rms times a multiple which has been specified by OPTION 17. The single-pass navigation output is shown in figure 12.

c. OPTION 14–Perform Solution Without Time Bias Adjustment. A multipass solution is performed in which the estimated parameters are the three components of the station position and a frequency offset for each pass. The output for this option is identical to the output generated by OPTION 19, except item 4 does not appear.

d. OPTION 19–Equipment Delay Adjustments. A multipass solution is performed in which the estimated parameters are the three components of the station position, a frequency offset for each pass, and one or more equipment delay parameters (paragraph 7). Provisions are made in the specification of this option which enable equipment delay parameters to be defined for either

- Each pass,
- Each satellite, or
- Each receiver.

Examples for the output of each of these are shown in figures 13 and 14. For the satellite or receiver, an equipment delay parameter is estimated for each different satellite or station code (pass identification card) found in the observation data deck used in the multipass solution.

e. OPTION 4–Plot Residuals. The observation residuals from a multipass solution can be plotted using this option. The output generated for a single pass is shown in figure 15.

f. OPTION 13–Pass Distribution Plots. The distribution of passes with respect to local station time and with respect to the tracking station (figure 16) can be generated with this option.

16. OUTPUT ERROR MESSAGES. Error messages produced by the preprocessors OBSIN and/or PROC are as follows:

a. ALL PASSES DELETED ***** RUN TERMINATED–No passes were output on drum by the preprocessor PROC.

b. DOPPLER AND EPHEMERIS ARE NOT CONSISTENT–PASS DELETED–Ephemeris points input to the preprocessor PROC are not increasing at 2-minute intervals.

c. DOPPLERS ARE MISSING–Doppler counts are missing for the quick check data type.

d. EPHEMERIS COEFFICIENTS MISSING FOR THIS PASS–The ephemeris data deck is missing for this pass.

e. ERROR IN EPHEMERIS INPUT–An error was detected in cards 2 to 5 of the ephemeris coefficient input. The coefficients were either missing or mispunched.

f. ERROR IN INPUT *** PASS DELETED–An error was detected while preprocessing the ephemeris input deck or Doppler input deck. The pass was deleted from further processing.

g. INPUT DATA SKIPPED–Input data cards were skipped in search for next pass observation deck.

h. INPUT ERROR–An error was detected while preprocessing the initializing constants deck. The card giving the error is printed.

i. LESS THAN XX DATA POINTS AFTER SEQUENCING *** PASS DELETED–This error occured in the preprocessor PROC while processing either Backpack or quick check data. There were less than XX data points after sequencing the observations in increasing order prior to matching them to the correct ephemeris intervals.

j. NUMBER OF SAMPLES EXCEEDS MAX ARRAY LENGTH–The number of ephemeris points evaluated for this pass exceeded 35, which is a preset program parameter for the maximum satellite points per pass. Additional Doppler observations for this pass are not used.

k. PASS XXXXXXXX IS FOR ANOTHER STATION–The station identification on the PASS identification card does not agree with the station identification on the STATION input card.

l. PREDICTED AND MEASURED DOPPLERS COULD NOT BE MATCHED–The preprocessor PROC could not match the observed Doppler counts to the predicted Doppler counts.

m. RUN MISSING EITHER STATION OR SPHEROID INPUT–This message results if the STATION or OPTION cards are missing from the initializing constants deck or if the STATION card specifies a datum type other than NWL and the corresponding SPHEROID card is missing.

```
                                                                                        DATE 030474        PAGE    4
                        GEOCEIVER WITH NWL EPHEMERIS

STATION              LATITUDE            LONGITUDE            ALTITUDE
                        X                    Y                    Z
(1) 30039         .389957741+002       .282687716+003       .741300000+002
                  .109020942+007      -.484248142+007       .399200373+007

(2) SPHEROID           A0                   B0               FLATTENING              SHIFTS NWL - ANDER
    ANDER         .637814500+007       .635675977+007       .335289187-002              0.     0.     0.

(3) CONSTANTS          C                    DT                   F0                 GEOID SEPARATION
                  .299792500+009       .000000000+000       .320000000+005         .000000000+000
(4) OPTIONS
        NUMBER OF ITERATIONS  5          RMS MULTIPLE  3           TROP CORRECTION  YES        SIGMA OBSERVATIONS   0
        SIGMA STATION LAT 0              SIGMA STATION LONG   0    SIGMA STATION ALT   0       LOCAL TIME DELETION  NO
        ELEVATION ANGLE CUTOFF  10

*******************************************************************************************************************
PASS  2284DYE            5/15/77            TIME  1720 HR/MN       REFRACTIVITY   263.8    86.7
(5)                    (6)          (7)                     (8)
NSMP      INPUT     CORRECTED   PREDICTED    ION   TROP   CI    PC   FL           SATELLITE EPHEMERIS (9)
                     DOPPLER     DOPPLER                                      X            Y            Z        HR MN   SEC
  1      872480      872480.     870841.     12.    1.  -13.  -1.   33    2396614.7   -5881740.7   3840653.2   17 20    .00000
  2      777226      777228.     770822.      8.    0.   -9.   0.   37    2339214.3   -5760878.1   4041262.3   17 20 32.20711
  3      935240      935240.     933598.      7.    0.   -8.  -2.   41    2288571.2   -5669153.4   4209962.9   17 20 59.81321
                                                                          2227878.0   -5546100.6   4402813.6   17 21 32.02032
  4     1018179     1018179.    1016536.      2.    0.   -1.   0.   46    2173812.4   -5434439.6   4566740.9   17 22    .00000
                                                                          2110117.9   -5300539.3   4751110.8   17 22 32.20711
  5     1104094     1104089.    1102446.     -3.   -0.    6.  -2.   46    2054344.9   -5181288.3   4905324.5   17 22 59.81321
  6      992186      992186.     990759.     -4.   -0.    8.   3.   43    1987984.2   -5037055.5   5080627.5   17 23 32.02032
  7     1174414     1174408.    1172767.     -7.   -0.   11.  -1.   40    1929272.7   -4907394.0   5228758.9   17 24    .00000
  8     1029402     1029397.    1027991.     -7.   -1.   12.  -0.   36    1860552.7   -4753253.3   5394329.0   17 24 32.20711
  9     1222212     1222203.    1220563.     -9.   -1.   15.  -2.   32    1800748.5   -4617077.7   5531916.9   17 24 59.81321
 10     1076593     1076590.    1075166.     -9.   -1.   14.   3.   28    1730008.9   -4453613.2   5687244.2   17 25 32.02032
 11     1252609     1252602.    1250983.    -11.   -1.   18.   0.   25    1667777.9   -4307708.6   5817531.3   17 26    .00000
 12     1082664     1082656.    1081252.    -11.   -1.   16.  -1.   21    1595335.1   -4135422.9   5962015.5   17 26 32.20711
 13     1271321     1271312.    1269674.    -13.   -2.   19.  -1.   18    1534620.4   -3984178.8   6081081.1   17 26 59.81321
 14     1110130     1110126.    1108703.    -13.   -2.   17.   2.   15    1458812.6   -3803716.3   6214295.3   17 27 32.02032
 15     1282973     1282965.    1281328.    -13.   -3.   20.   2.   13    1394202.1   -3643566.8   6324948.7   17 28    .00000
                                                                          1319349.1   -3458500.2   6446366.4   17 28 32.20711
(10) GEOCEIVER LOCAL CLOCK EPOCH ERROR    5.511 MS    SIGMA     .042 MS
(11) EPHEMERIS COEFFICIENTS
TOTAL DELETIONS  0         OFFSET FREQUENCY   .320000000+005       LOCAL TIME 1210 HR/MN      LO =  .749541210+000
*******************************************************************************************************************
```

(1) Station number and location as specified on STATION card.

(2) Spheroid parameters and datum shift as specified on DATUM card.

(3) Constants as specified on CONSTANTS card.

(4) Values for selected options as input on OPTIONS card.

(5) Sequential number of observations. An observation without a sample number indicates a preprocessor deleted observation.

(6) Input Doppler count corrected for ionospheric and tropospheric refraction, C1, and PC.

(7) A predicted Doppler count determined using the satellite ephemeris and the input station coordinate.

(8) Magnitude of corrections applied to the input Doppler count in cycles.

(9) The position of the satellite at the beginning of the observation.

(10) The epoch error ($\overline{CE}$) in the local clock as defined in paragraph 6.

(11) *Indication of the input representation of the satellite ephemerides;* either ephemeris coefficients, points, or satellite message.

Figure 7. Preprocessor output.

①		②	③		④		⑤		⑥
PASS	NUMBER	CODE	EAST	NORTH	NORTH	UP	EAST	UP	
22840YF	1	A	7.	-1.	13.	-4.	-3.	5.	NORTH
22841YF	2	B	-2.	-2.	-8.	-9.	-2.	2.	NORTH
22853YF	3	C	-6.	7.	-28.	31.	9.	-9.	NORTH
22854YF	4	D	2.	5.	120.	56.	5.	-1.	NORTH
22867YF	5	E	-0.	-3.	23.	-10.	-3.	-0.	NORTH
ROOT MEAN SQUARE			4.	4.	56.	29.	5.	5.	
⑦ PLOT DELETION GATE			18.	18.	191.	191.	21.	21.	

① Pass identification.
② Pass code for printer plots (figures 9, 10, and 11).
③ East and North components of single-pass navigation solutions with height constrained to input value.
④ North and up (height) components of single-pass navigation solutions with station constrained to be in meridian plane of input coordinate.
⑤ East and up components of single-pass navigation solutions with station constrained to be in cross meridian plane of input coordinate.
⑥ Direction of pass.
⑦ Deletion gate used for plots in figures 7, 8, and 9.

Figure 8. Single-pass navigation solution summary.

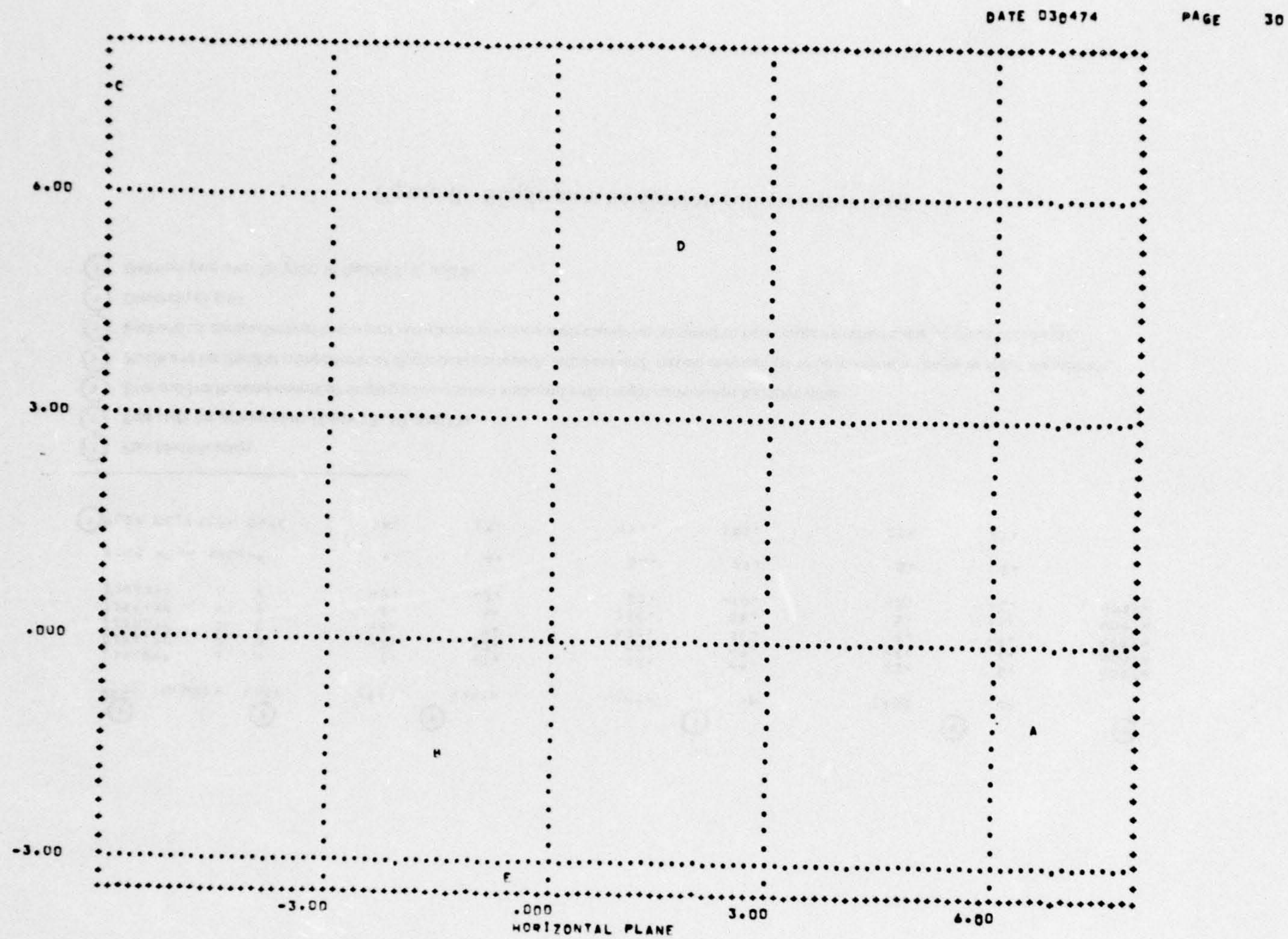

Figure 9. Single-pass navigation solution plot—height constrained.

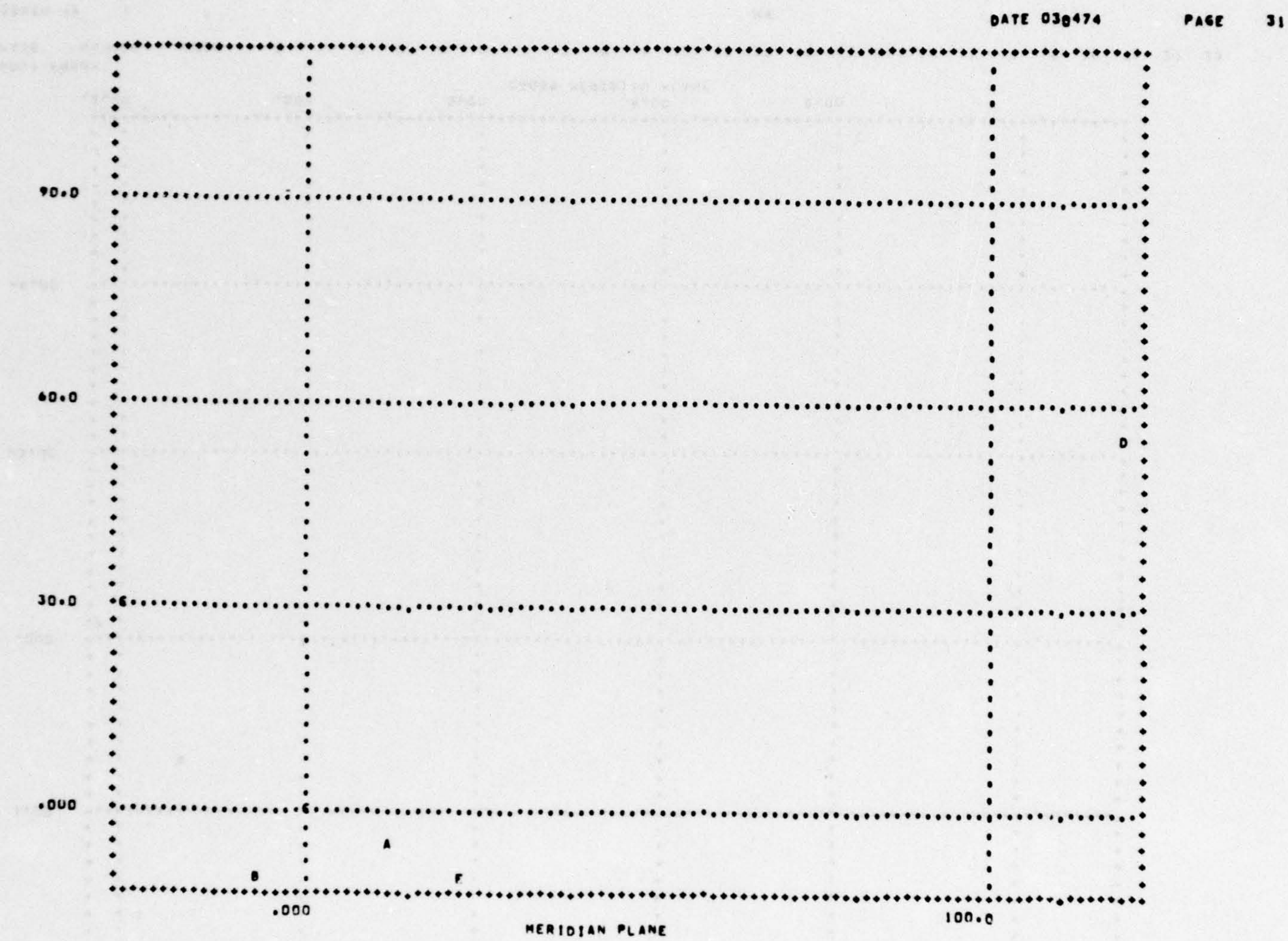

Figure 10. Single-pass navigation solution plot–longitude constrained.

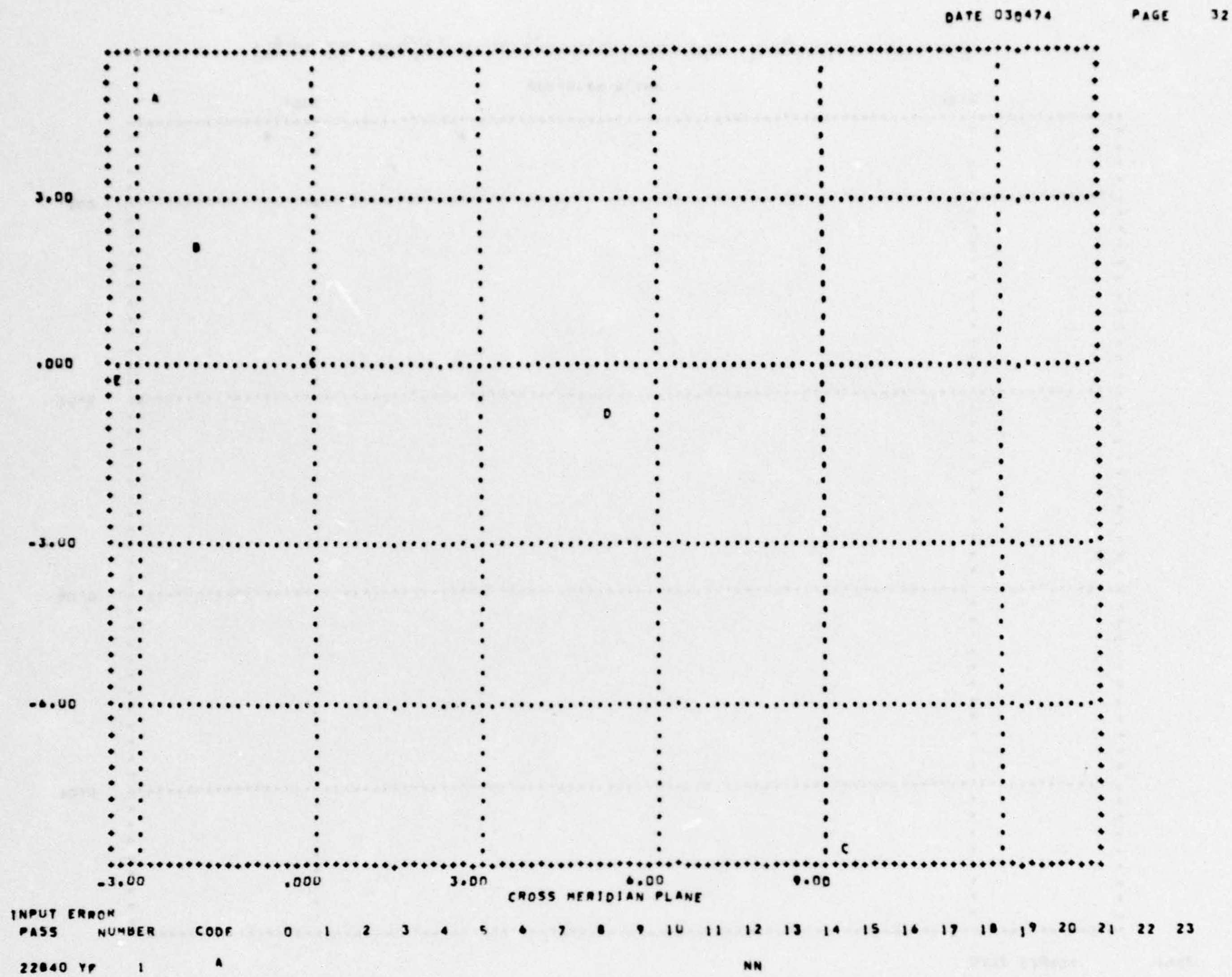

Figure 11. Single-pass navigation solution plot—latitude constrained.

```
PASS BY PASS DOPPLER SOLUTION FOR PASS 2284OYF

            ITERATION                             1                                  2                                  3
      RMS  ( COUNT  )                             0.                                 0.                                 0.
      RMS  ( METERS )          (1)                0.                                 0.                                 0.
      DEGREES OF FREEDOM                         12                                 12                                 12
            DELETION GATE                         1.                                 1.                                 1.

                            VALUE           DELTA       SIGMA     VALUE         DELTA       SIGMA     VALUE         DELTA       SIGMA
      FREQUENCY OFFSET    1923049.          3049.        0.     1923049.        -0.          0.     1923049.        -0.          0.
               X METERS   1090219.   (2)       9.        1.     1090219.         0.          1.     1090219.        -0.          1.
               Y METERS  -4842499.           -17.        1.    -4842499.        -0.          1.    -4842499.        -0.          1.
               Z METERS   3991987.           -17.        1.     3991987.         0.          1.     3991987.         0.          1.
   1        1640.           1229.                       -0.                   -0.                  -0.             -0.
   2        1406.           1054.                       -0.                   -0.                  -0.             -0.
   3        1641.           1230.                        0.                    0.                   0.              0.
   4        1643.           1231.                        0.                    0.                   0.              0.
   5        1643.           1231.                        0.                    0.                   0.              0.
   6        1426.    (3)    1069.                        0.                    0.                   0.              0.
   7        1641.           1230.                       -0.                   -0.                  -0.             -0.
   8        1406.           1054.                       -0.                   -0.                  -0.             -0.
   9        1639.           1229.                       -0.                   -0.                  -0.             -0.
  10        1424.           1067.                       -0.                   -0.                  -0.             -0.
  11        1638.           1228.                       -0.                   -0.                  -0.             -0.
  12        1404.           1053.                        0.                    0.                   0.              0.
  13        1638.           1228.                        0.                    0.                   0.              0.
  14        1423.           1067.                        0.                    0.                   0.              0.
  15        1638.           1227.                        0.                    0.                   0.              0.
```

(1) Solution statistics for first iteration of navigation.

(2) Current values of solution parameters and change from previous iteration. For iteration 1, the change DELTA is computed with respect to the input values of the parameters.

(3) Observation residuals in counts and in meters prior to iteration 1.

Figure 12. Single-pass navigation solution.

MULTI-PASS SOLUTION FOR STATION 30039

A TIME BIAS WILL BE CALCULATED FOR EACH PASS
TROP CORRECTIONS WILL BE USED
ONLY SOUTH GOING PASSES WILL BE USED
SAMPLES WITH ELEVATION ANGLES < 10 WILL BE DELETED
IONOSPHERIC CORRECTIONS WILL BE USED

1

ITERATION 1 RESIDUAL RMS .14 NUMBER OF EQUATIONS 53 NUMBER OF PASSES 3 NUMBER OF DEGREES OF FREEDOM 44

	3 ORIGINAL	TOTAL CHANGE	THIS ITER	3 NEW		2 ORIGINAL (ANDER DATUM)		TOTAL CHANGE	THIS ITER	3 NEW	
X	1090217.23	-5.97	-5.97	1090211.27	PHI	38 59	43.795	17.02	17.02	38 59	44.347
Y	-4842499.65	8.54	8.54	-4842491.10	LAMBDA	282 41	15.928	-3.95	-3.95	282 41	15.764
Z	3991979.88	14.10	14.10	3991993.97	HEIGHT		74.27	1.37	1.37		75.65

ITERATION 2 RESIDUAL RMS .14 NUMBER OF EQUATIONS 53 NUMBER OF PASSES 3 NUMBER OF DEGREES OF FREEDOM 44

THE DELETION GATE IS 0.

	ORIGINAL	TOTAL CHANGE	THIS ITER	NEW		ORIGINAL (ANDER DATUM)		TOTAL CHANGE	THIS ITER	NEW	
X	1090217.23	-5.97	-.00	1090211.27	PHI	38 59	43.795	17.02	.00	38 59	44.347
Y	-4842499.65	8.54	.00	-4842491.10	LAMBDA	282 41	15.928	-3.95	-.00	282 41	15.764
Z	3991979.88	14.10	.00	3991993.97	HEIGHT		74.27	1.38	.00		75.65

PASS 22846

NUMBER	DOPPLER	TROP	IONO	ALTITUDE	DELTA T	RESIDUAL	METERS	PERT
33	848875.6	2.4	4.0	10	32.2071	-.21	-.16	.0
34	736854.9	1.6	3.4	12	27.6061	-.03	-.02	.0
35	872191.2	1.5	2.0	13	32.2071	-.26	-.19	.0
36	770255.5	1.0	-1.6	15	27.9797	.17	.12	.0
37	903143.8	.9	-5.9	17	32.2071	.07	.05	.0
38	789921.6	.6	-2.0	19	27.6061	.21	.16	.0
39	942094.0	.5	-10.1	20	32.2071	.21	.15	.0
40	837975.4	.3	-12.0	21	27.9797	.07	.06	.0
41	988684.0	.2	-15.6	22	32.2071	.01	.01	.0
42	868880.5	.1	-13.4	23	27.6061	.07	.05	.0
43	1039208.2	-.0	-15.2	23	32.2071	-.15	-.11	.0
44	924974.4	-.1	-11.5	23	27.9797	-.27	-.21	.0
45	1089437.2	-.3	-14.5	22	32.2071	-.03	-.02	.0
46	953742.2	-.4	-16.8	22	27.6061	-.05	-.04	.0
47	1134199.8	-.6	-29.3	21	32.2071	-.10	-.07	.0
48	1002447.2	-.7	-24.1	19	27.9797	.11	.09	.0
49	1171485.4	-1.0	-29.3	18	32.2071	.03	.02	.0
50	1017401.2	-1.1	-23.0	16	27.6061	.00	.00	.0
51	1200474.5	-1.6	-20.9	14	32.2071	.19	.14	.0
52	1053192.7	-1.8	-19.9	13	27.9797	-.00	-.00	.0

4

PASS 22860

RESIDUALS REPEATED FOR EACH PASS

RESIDUALS REPEATED FOR EACH PASS

```
.....................................................................................................................
ITERATION  3    RESIDUAL RMS   .14    NUMBER OF EQUATIONS   53    NUMBER OF PASSES   3    NUMBER OF DEGREES OF FREEDOM   44
                                            UNDER  DATUM
                                      THE DELETION GATE IS        0.
     ORIGINAL      TOTAL    THIS         NEW                 ORIGINAL              TOTAL   THIS            NEW
                   CHANGE   ITER                                                   CHANGE  ITER
X   1090217.23     -5.97    -.00   1090211.27       PHI     38 59    43.795      17.02    .00    38 59    44.347     5
Y  -4842499.65      8.54     .00  -4842491.10    LAMBDA    282 41    15.928      -3.95   -.00   282 41    15.764
Z   3991979.88     14.10     .00   3991993.97    HEIGHT              74.27        1.38    .00              75.65
                                              CORRELATION MATRICES
                            GEOCENTRIC                                   LOCAL
                       1.000   -.886   -.954                   1.000   -.836    .649
                       -.886   1.000    .980                   -.836   1.000   -.887
                       -.954    .980   1.000                    .649   -.887   1.000

.....................................................................................................................
                                        FREQUENCY OFFSET                                    EQUIPMENT DELAY
        PASS       ORIGINAL          CHANGE          NEW           ERROR             TIME BIAS     ERROR       4
        22846      1920000.0         3050.02      1923050.02        .23               1.787        1.551
        22860      1920000.0         3051.95      1923051.94        .10               2.057        1.430
        22861      1920000.0         3049.79      1923049.78       1.19               4.019         .793
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   0           0           0           0           0           0           0
- - - - - - - - - - - - - - - - - - - - - -  PASS   22846  - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

1. An indication of the various options selected for this multipass solution. The selection of OPTIONS 10, 15, 16, 18, 20, and 26 will be indicated for each multipass solution.
2. The starting values of the coordinates of the station for this multipass solution. If OPTION 12 is 0 or 2, this will correspond to the input value of the station coordinate. If OPTION 12 is 1, the new value of the station coordinate from a previously executed multipass solution will be used.
3. The adjusted or new station coordinate after the first iteration.
4. *Observation residuals in counts and meters for pass* **22846** based on the new values from iteration 2.
5. **Solution results for the last iteration (in this example, only 3 iterations were performed).**
6. In addition to the frequency offset, the adjusted equipment delay for each pass is shown in milliseconds.

Figure 13. Multipass solution with equipment delay estimated for each pass.

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MULTI-PASS SOLUTION FOR STATION 30039

A TIME BIAS WILL BE CALCULATED FOR EACH SATELLITE
IONOSPHERIC CORRECTIONS WILL BE USED
TROP CORRECTIONS WILL BE USED
SAMPLES WITH ELEVATION ANGLES < 10 WILL BE DELETED

ITERATION 1 RESIDUAL RMS .27 NUMBER OF EQUATIONS 140 NUMBER OF PASSES 8 NUMBER OF DEGREES OF FREEDOM 128

ANDER DATUM

	ORIGINAL	TOTAL CHANGE	THIS ITER	NEW		ORIGINAL		TOTAL CHANGE	THIS ITER	NEW	
X	1090209.42	1.11	1.11	1090210.53	PHI	38 59	44.794	-11.83	-11.83	38 59	44.410
Y	-4842481.42	-9.18	-9.18	-4842490.60	LAMBDA	282 41	15.777	-.93	-.93	282 41	15.738
Z	3992003.73	-7.78	-7.78	3991995.95	HEIGHT		74.13	2.25	2.25		76.38

EQUIPMENT DELAY

NEW	CORRECTION	ERROR	SYMBOL
1.78283	1.78283	.07194	Y

ITERATION 2 RESIDUAL RMS .26 NUMBER OF EQUATIONS 139 NUMBER OF PASSES 8 NUMBER OF DEGREES OF FREEDOM 127

ANDER DATUM
THE DELETION GATE IS 1.

	ORIGINAL	TOTAL CHANGE	THIS ITER	NEW		ORIGINAL		TOTAL CHANGE	THIS ITER	NEW	
X	1090209.42	1.28	.17	1090210.70	PHI	38 59	44.794	-12.06	-.22	38 59	44.403
Y	-4842481.42	-9.25	-.07	-4842490.67	LAMBDA	282 41	15.777	-.78	.15	282 41	15.745
Z	3992003.73	-7.98	-.20	3991995.75	HEIGHT		74.13	2.21	-.04		76.34

EQUIPMENT DELAY

NEW	CORRECTION	ERROR	SYMBOL
1.81938	.03655	.06970	Y

PASS 22840

NUMBER	DOPPLER	TROP	IONO	ALTITUDE	DELTA T	RESIDUAL	METERS	PERT
1	872480.3	.6	12.4	33	32.2071	-.67	-.51	.0
2	772227.8	.4	7.9	37	27.6061	-.38	-.28	.0
3	935239.6	.3	6.7	41	32.2071	-.28	-.21	.0
4	1018178.7	.1	1.9	46	32.2071	.14	.10	.0
5	1104088.9	-.2	-2.9	46	32.2071	.50	.38	.0
6	992185.8	-.3	-4.5	43	27.9797	.41	.30	.0
7	1174408.0	-.5	-6.5	40	32.2071	-.05	-.04	.0
8	1029396.6	-.5	-6.9	36	27.6061	.20	.15	.0
9	1222202.8	-.8	-9.2	32	32.2071	.00	.00	.0
10	1076589.8	-.8	-9.4	28	27.9797	.06	.05	.0
11	1252601.7	-1.2	-11.1	25	32.2071	-.16	-.12	.0
12	1082656.4	-1.2	-10.6	21	27.6061	.09	.07	.0
13	1271311.7	-1.8	-12.9	18	32.2071	.05	.04	.0
14	1110125.7	-2.0	-13.0	15	27.9797	.16	.12	.0
15	1282965.4	-3.1	-13.2	13	32.2071	-.01	-.01	.0

PASS 22841

NUMBER	DOPPLER	TROP	IONO	ALTITUDE	DELTA T	RESIDUAL	METERS	PERT
.								.
.								.
.								.

RESIDUALS REPEATED FOR EACH PASS

RESIDUALS REPEATED FOR EACH PASS

```
..........................................................................................................................
ITERATION  3     RESIDUAL RMS   .24     NUMBER OF EQUATIONS  138     NUMBER OF PASSES   8     NUMBER OF DEGREES OF FREEDOM  126

                                          ANDER  DATUM
                                      THE DELETION GATE IS        1.
    ORIGINAL       TOTAL      THIS          NEW                  ORIGINAL              TOTAL    THIS          NEW
                   CHANGE     ITER                                                     CHANGE   ITER
X  1090209.42       .89      -.39    1090210.31        PHI     38 59    44.794       -12.30    -.24    38 59    44.395
Y -4842481.42     -9.80      -.55   -4842491.22      LAMBDA   282 41    15.777        -1.28    -.50   282 41    15.724   (6)
Z  3992003.73     -7.92       .06    3991995.81      HEIGHT             74.13          2.60     .39             76.73
                                            CORRELATION MATRICES
                          GEOCENTRIC                                 LOCAL
                   1.000     .406    -.183                  1.000     .069    -.171
                    .406    1.000     .001                   .069    1.000    -.335
                   -.183     .001    1.000                  -.171    -.335    1.000

..........................................................................................................................
                                    EQUIPMENT DELAY
                 NEW         CORRECTION         ERROR          SYMBOL
               1.86425         .04488           .06737            Y

                                            FREQUENCY OFFSET
                    PASS          ORIGINAL        CHANGE         NEW          ERROR

                    22840        1920000.0       3049.75     1923049.73        .19
                    22841        1920000.0       3048.49     1923048.48        .18
                    22846        1920000.0       3049.63     1923049.62        .17
                    22853        1920000.0       3051.08     1923051.08        .17     (7)
                    22854        1920000.0       3050.38     1923050.37        .14
                    22860        1920000.0       3051.88     1923051.87        .18
                    22861        1920000.0       3052.20     1923052.20        .21
```

---

(1) An indication of the various options selected for this multipass solution. The selection of OPTIONS 10, 15, 16, 18, 20, and 26 will be indicated for each multipass solution.

(2) The starting values of the coordinates of the station for this multipass solution. If OPTION 12 is 0 or 2, this will correspond to the input value of the station coordinate. If OPTION 12 is 1, the new value of the station coordinate from a previously executed multipass solution will be used.

(3) The adjusted or new station coordinate after the first iteration.

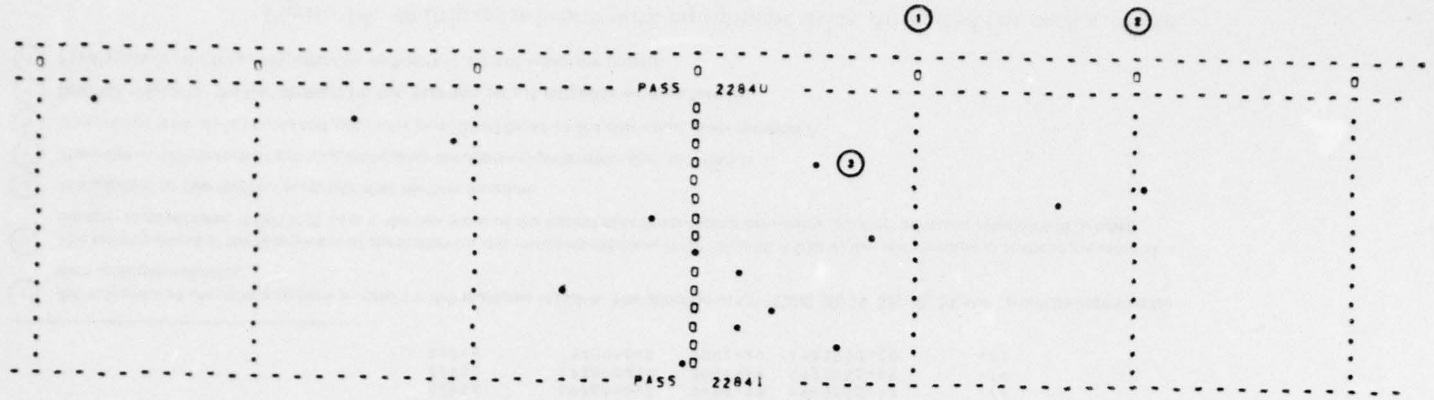
(4) The value in milliseconds of the equipment delay parameter or parameters after iteration 1.

(5) Observation residuals in counts and meters for pass 22840 based on the new values from iteration 2.

(6) Solution results for the last iteration (in this example, only 3 iterations were performed).

(7) Final values for the frequency offset for each pass in units of cycles per minute.

Figure 14. Multipass solution with equipment delay estimated for each satellite.



(1) One-sigma level which corresponds to the rms of the last iteration in counts.

(2) Two-sigma level.

(3) The residual of the fourth observation.

Figure 15. Multipass solution residual plot.

```
TOTAL NUMBER OF PASSES INPUT      8
TOTAL NUMBER OF PASS DELETIONS     0
TOTAL NUMBER OF POINT DELETIONS     0
```

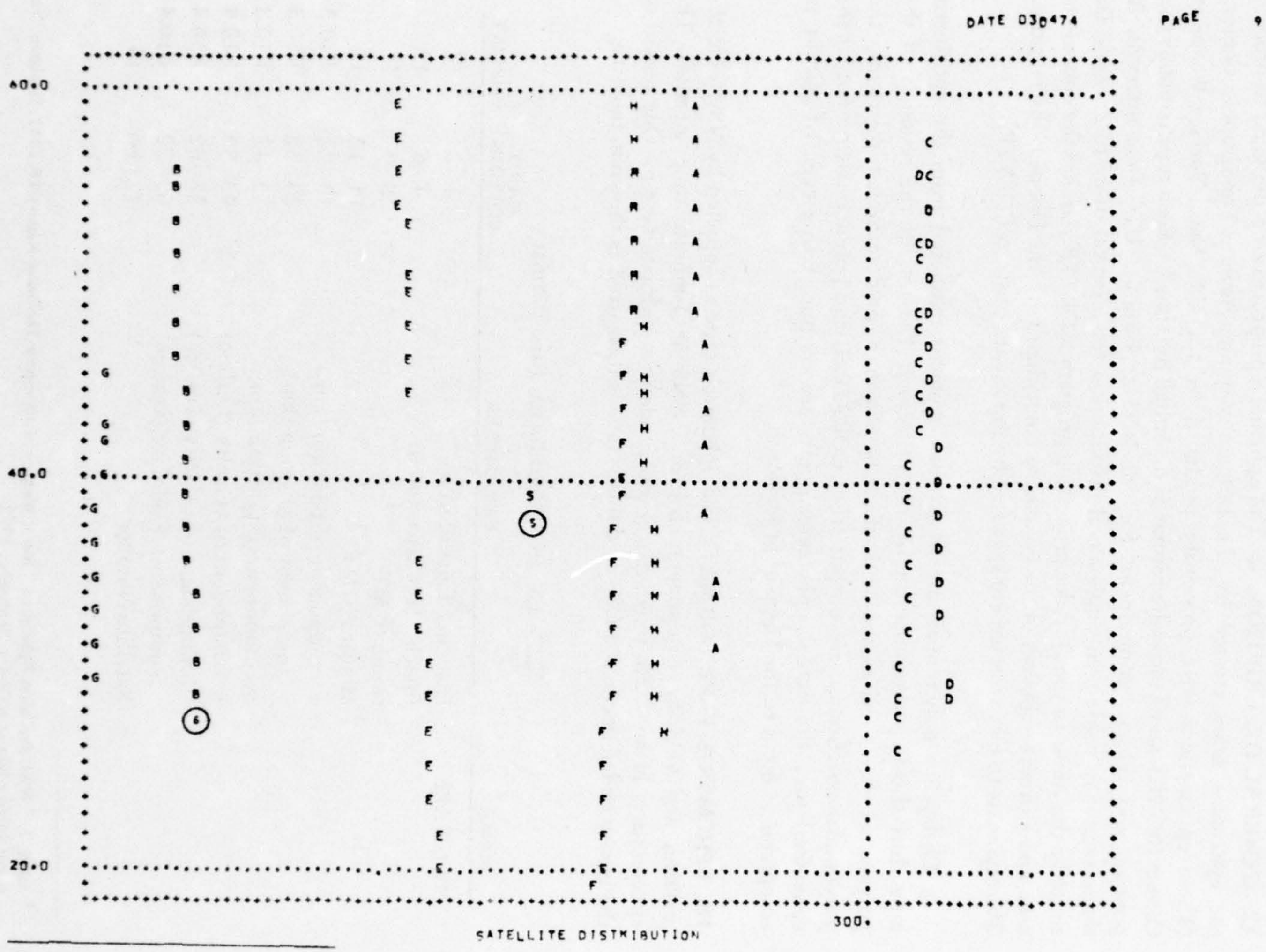
PASS (1)	NUMBER (2)	CODE (3)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
22840 YF	1	A													NN											
22841 YF	2	B														NN										
22846 YF	3	C																								SS
22853 YF	4	D												NN												
22854 YF	5	E														NN										
22860 YF	6	F	SS																							
22861 YF	7	G			SS (4)																					
22867 YF	8	H													NN											

(1) Pass identification.

(2) Sequential number of pass.

(3) Pass code for satellite distribution plot.

(4) Indication that pass 22861YF was a northgoing to southgoing pass which occurred between 0200 and 0300 hours local time.



(5) Station position.

(6) Subsatellite points of pass 22840YF.

Figure 16. Pass distribution plots.

SECTION IV. EPHEMERIS PREPROCESSOR

17. GENERAL DESCRIPTION. *a.* The ephemeris preprocessor is designed to process the ephemeris tapes created by the Defense Mapping Agency Topographic Center. (These ephemerides were previously produced by the U.S. Naval Surface Weapons Center [NSWC] and follow the format as described by Sims[5]). Each tape contains the position and velocity components for one NNS at 1-minute UTC time intervals. A single tape may contain this ephemeral information for a period of up to 2 weeks. To simplify the input to the Doppler processing program, COPYTP searches the ephemeris tape and extracts segments of the ephemeris coincident with the Doppler observations. The segments to be extracted are specified by input data cards to COPYTP.

b. Chebychev polynomials are fit to each segment extracted from the ephemeris tape thus allowing interpolation by the processor. The rms of the residuals of the polynomial fit is calculated and, if it is within a predetermined tolerance, the polynomial coefficients are output from COPYTP. If the polynomials do not fit the ephemeral arc, the actual ephemeris points are output. Either type of output is acceptable as input to the Doppler processor.

18. EPHEMERIS TAPE FORMAT. The ephemeris tape as supplied by NSWC has the position and velocity components for one NNS at 1-minute time intervals. The ephemeris is in an Earth-fixed geocentric geodetic coordinate system. One record of the binary coded decimal (BCD) card image tape is formatted as shown in table 13.

Table 13. BCD Card Image Tape Format

NAME	PARAMETER	CARD COLUMN	FORMAT
NWL TAPE	Last two digits of year	1–2	I2
	Epoch (days since Jan 0)	4–6	I3
	Hours (GMT)	8–9	I2
	Minutes (GMT)	11–12	I2
	x component of position (km)	13–22	F10.3
	y component of position (km)	23–32	F10.3
	z component of position (km)	33–42	F10.3
	x component of velocity (km/sec)	43–52	F10.4
	y component of velocity (km/sec)	53–62	F10.4
	z component of velocity (km/sec)	63–72	F10.4
	Satellite Number	77–80	I4

[5] SIMS, T. "NWL Precision Ephemeris," *Naval Weapons Laboratory Technical Report* TR 2842. Dahlgren, Va.: Naval Surface Weapons Center. September 1972.

19. **DATA DECK STRUCTURE.** *a. Ephemeris Preprocessor Run Deck.* The run deck structure for the ephemeris preprocessor COPYTP is shown in figure 17. PROG is the program tape and DAP26 is the NSWC ephemeris tape.

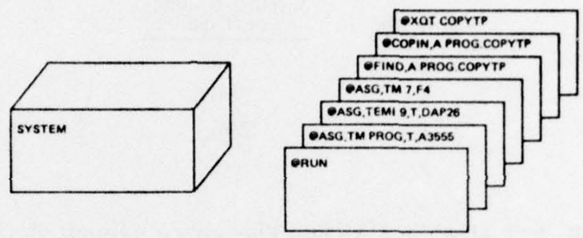


Figure 17. Deck structure for COPYTP.

b. Input Data Cards. As input, COPYTP requires a data deck consisting of one card for each segment of the ephemeris to be punched. Each data card has the format shown in table 14. The maximum number of data cards is set at 100. The data cards can specify a mixture of satellites and ephemeral times. COPYTP reads the first record of the tape and determines the starting epoch and satellite on the tape. The epoch and satellite of each data card is compared to the tape parameters and the cards for satellites and times not on the tape are skipped. The remaining cards are sorted by increasing epoch. The requested arcs are then sequentially extracted from the tape.

Table 14. COPYTP Data Card Format

CARD NAME	PARAMETER	CARD COLUMN	FORMAT
DATA CARD	Termination Symbol	1	I1
	= 0 normally		
	= 9 last card of data deck		
	Orbit Number	2–7	A6
	Satellite Identification	8	A1
	Ephemeris Segment Epoch (GMT)		
	Month	12–13	I2
	Day	14–15	I2
	Year	16–17	I2
	Hour	18–19	I2
	Minute	20–21	I2

20. OUTPUT ERROR MESSAGES. *a.* SATELLITE XXX NOT FOUND IN TABLE (DATA CARD)–The satellite code in the pass ID is in error. The correct satellite identification–satellite number correspondence is defined as:

Card Code	Satellite Number on Tape
w	––
x	2807
y	2965
z	––

b. *** ERROR *** (DATA CARD)–The epoch requested on the data card is earlier than the starting epoch on the tape.

c. NO DATA–The data has been sorted and none of the requested ephemeris segments are on the tape that has been mounted.

d. *** PASS XXXXXX COULD NOT BE LOCATED–The requested segment should be on the tape; however, it could not be found.

e. EOF ON TAPE–End of file encountered on tape–last record on tape is printed out.

f. INPUT ERROR XX STATEMENT Y–Type XX input error occurred in a record to be skipped at statement Y in the program. Recoverable.

g. INPUT CARD ERROR–A LAPUN data card is in error–card is skipped.

h. CARD EOR–The termination (end of record) symbol is missing in the LAPUN data deck.

SECTION V. SUMMARY

The DOPPLR Point Positioning Program has been in production use at the DMA Topographic Center for the past 5 years. It has proven to be a reliable software program and takes advantage of all the inherent accuracy present in the Doppler observations from the portable Doppler receivers. It has also been used as a simulation tool to determine expected geodetic accuracies under various operational configurations and constraints. This capability has proven to be useful in planning Doppler operations to support both mapping and precise geodetic applications.